CCM-79-11

Center for Composite Materials

COMPUTATIONAL ALGORITHMS FOR PREDICTING THE MECHANICAL PROPERTIES OF SHEET MOLDING MATERIALS

G. JARZEBSKI
S. MCGEE
P. MROZ

ADVISOR: R. L. MCCULLOUGH

College of Engineering
University of Delaware
Newark, Delaware

*MSG DI4 DROLS PROCESSING - LAST INPUT IGNORED

-- 1 OF 1

-- ***DTIC DOES NOT HAVE THIS ITEM***

-- 1 - AD NUMBER: D429747

-- 5 - CORPORATE AUTHOR: DELAWARE UNIV NEWARK CENTER FOR COMPOSITE
-- MATERIALS

-- 6 - UNCLASSIFIED TITLE: COMPUTATIONAL ALGORITHMS FOR PREDICTING THE
-- MECHANICAL PROPERTIES OF SHEET MOLDING MATERIALS,

--10 - PERSONAL AUTHORS: JARZEBSKI,G. ;MCGEE,S. ;MROZ,P. ;

--11 - REPORT DATE: JUN , 1979

-12 - PAGINATION: 109P

--14 - REPORT NUMBER: CCM-79-11

--20 - REPORT CLASSIFICATION: UNCLASSIFIED

--22 - LIMITATIONS (ALPHA): APPROVED FOR PUBLIC RELEASE; DISTRIBUTION
-- UNLIMITED. AVAILABILITY: CENTER FOR COMPOSITE MATERIALS, COLLEGE OF
-- ENGINEERING, UNIVERSITY OF DELAWARE, NEWARK, DELAWARE 19711.

--33 - LIMITATION CODES: 1 24

--******

-- END OF DISPLAY LIST

-- <<ENTER NEXT COMMAND>>

Alt-Z FOR HELP3 ANSI 3 HDX 3 3 LOG CLOSED 3 PRINT OFF 3 PARITY

COMPUTATIONAL ALGORITHMS FOR PREDICTING THE MECHANICAL PROPERTIES OF SHEET MOLDING MATERIALS

by

G. Jarzebski
S. McGee
P. Mroz

Advisor: R. L. McCullough

June 1979

TABLE OF CONTENTS

INTRODUCTION

The recent demands on the automotive industry for weight-saving have focused attention on the use of polymeric materials reinforced by short lengths of reinforcing fibers. These short fiber composite systems can be molded to give rigid, lightweight structural components. The utilization of these materials in load-bearing applications necessarily directs attention to their mechanical properties and, in particular, to the role that processing plays in establishing the mechanical performance of these multicomponent materials.

Unlike the traditional materials of construction, these heterogeneous materials exhibit a wide range of properties which are dependent on the initial fiber/resin/filler composition as well as the particular internal microstructure developed during fabrication. This sensitivity to processing is manifest in both the magnitude and directional dependence of the mechanical, thermal, electrical, and transport properties.

The wide range of possible compositions, fiber length distributions, and fiber orientation distributions that may be utilized in and generated during the manufacture of components from these materials precludes a total reliance on direct laboratory characterization of the anisotropic mechanical properties. Consequently, constitutive relationships which connect the composition and processing dependent microstructure to mechanical performance are an important component of the technology for short fiber composite materials.

Constitutive relationships for unidirectional continuous fiber laminates are reasonably well developed. For this special material system, the continuity of the fiber assures that the strain field parallel to the aligned fibers is essentially uniform. However, the stress and strain field transverse to the fiber directions will vary within the body. Consequently,

the major difficulty in predicting the behavior of continuous fiber systems is associated with predicting the Transverse Young's Moduli and Shear Moduli. The situation for short fiber composites is considerably more complex. Even if all the fibers were perfectly aligned, the discontinuities would cause fluctuations in the stress and strain fields parallel to the fiber axes.

Recently, Wu and McCullough (Development in Composite Materials, Applied Science Publishers, London, 1977) developed improved variational treatments which provide general bounding relationships for the effective elastic properties of a wide variety of heterogeneous materials, viz, polycrystalline metals, crystalline polymers, continuous fiber reinforced composites, short fiber composites, and particulate reinforced polymers. Upon the specification of certain parameters, the bounding relationships yield families of specific constitutive relationships which contain all reported models as special cases. As would be expected, such general constitutive relationships are somewhat complex. Accordingly, it is useful to introduce simplifications that can yield reasonable engineering estimates while reducing the computational effort required to obtain estimates for the anisotropic Young's moduli and Shear moduli.

Considerable simplification has been achieved through the use of an "Aggregate Model." The important features of the Aggregate Model are described in a subsequent section. In essence, the Aggregate Model treats a short fiber composite as a "grainy metal" in which the properties of the individual grains are averaged over an orientation distribution to yield the effective properties of the bulk material. Even with this simplification, the computational effort remains tedious. Consequently, computer algorithms have been developed to facilitate the prediction of properties from a knowledge of the composition, state of orientation, and the aspect ratio of the fibers of a sheet molding material. Two computational tools have been developed: (1) an interactive FORTRAN routine for general use, and (2) a restricted routine for use on hand-held calculators such as the Texas Instrument TI-59.

27

In the following sections the elements of material modeling are reviewed and ~~the~~ an Aggregate Model was developed as an introduction to the notation used in the subsequent documentation of the computational routine. Examples are provided to illustrate the use of the computational tools.

author, modified

BACKGROUND

Before proceeding with the development of models for predicting the behavior of sheet molding materials in terms of composition, fiber geometry and fiber orientation, it will be useful to briefly review the basic principles and notations used for the description of the mechanical behavior of materials. For this purpose, attention will be first directed to the general characterization of the load-deformation response of homogeneous (single component) materials. These results will be used in subsequent sections to develop the effective load-deformation characteristics of heterogeneous (multicomponent) materials.

Generalized Materials Descriptors

The load-deformation response characteristics of an isotropic material (e.g., an amorphous polymer) are traditionally described by the Engineering constants: The Young's modulus, E; the Shear modulus, G; and Poisson's ratio, ν. The Young's modulus is used to indicate the ability of a material to transfer a pure extension strain (ε) into a pure tensile stress (σ); the Poisson's ratio is used to describe the extent to which the lateral dimensions of a body decrease in response to a pure extensional strain. The Shear modulus is used to describe the ability of a material to transfer a pure shear strain (γ) into a pure shear stress (τ). For isotropic materials, these descriptors are not independent. It can be shown that if the material properties are the same in all directions, then the Engineering constants are related through $G = E/[2(1+\nu)]$.

Many material systems (e.g., drawn polymers, continuous fiber reinforced composites) exhibit properties that vary with the direction in which the load (or deformation) is applied. For the current considerations, materials with orthotropic symmetry are the class of materials with the lowest symmetry

that need be considered. Orthotropic symmetry is characteristic of materials whose properties are equivalent across three mutually perpendicular planes. For materials of this symmetry class, it is necessary to characterize the load-deformation response characteristics along three directions of the material (e.g., the longitudinal, transverse, and perpendicular axis). The notation and load-deformation descriptions for the three distinct Young's moduli and the three distinct Shear moduli are schematically defined in Figure 1.

In the Theory of Elasticity (which provides the theoretical basis for the analysis of the mechanical behavior of materials), alternate sets of material descriptors are used: the compliance array, $\underset{\approx}{S}$, and the elastic constant array, $\underset{\approx}{C}$. The compliance array is used to describe the various deformations that result from the application of combined (or individual) loads. The elastic constant array is used to describe the various stresses that result from a general deformation. In the generalized notation, the tensile strain in the "1" direction that results from tensile stresses in the "1", "2", and/or "3" direction are given by

$$\varepsilon_1 = S_{11}\,\sigma_1 + S_{12}\,\sigma_2 + S_{13}\,\sigma_3$$

Similarly,

$$\varepsilon_2 = S_{21}\,\sigma_1 + S_{22}\,\sigma_2 + S_{23}\,\sigma_3$$

$$\varepsilon_3 = S_{31}\,\sigma_1 + S_{32}\,\sigma_2 + S_{33}\,\sigma_3$$

with $S_{ij} = S_{ji}$.

The shear deformations (γ) are related to the shear stresses (τ) by the relationships

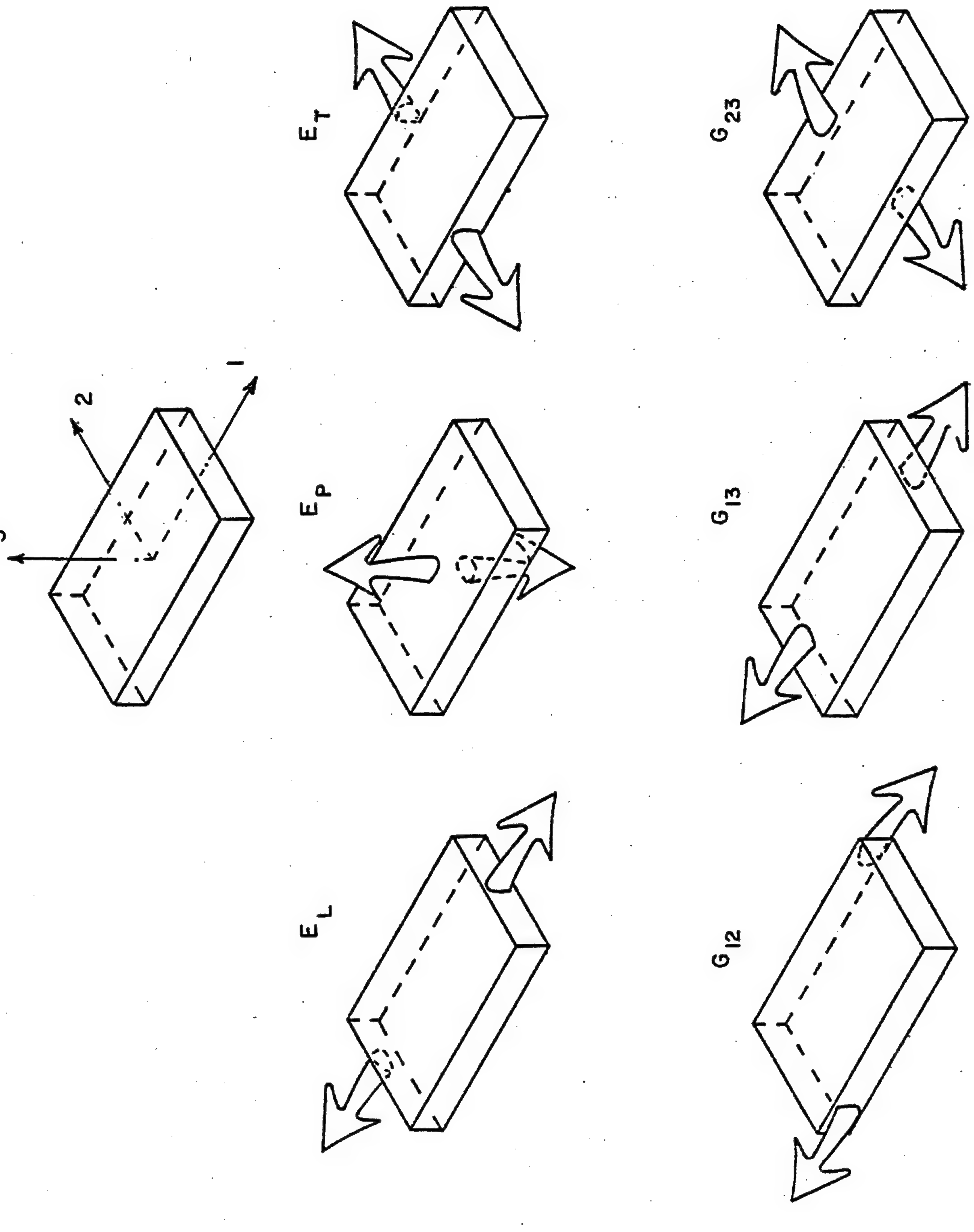
$$\gamma_{23} = S_{44}\,\tau_{23}$$

$$\gamma_{13} = S_{55}\,\tau_{13}$$

$$\gamma_{12} = S_{66}\,\tau_{12}$$

FIGURE 1

Schematic Definition of the Distinct Young's Moduli and Shear Moduli for Materials of Orthotropic Symmetry



3
2
1
E_P
E_T
E_L
G_13
G_23
G_12

These six relationships can be written in compact matrix form as

$$\begin{vmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \varepsilon_{23} \\ \varepsilon_{13} \\ \varepsilon_{12} \end{vmatrix} = \begin{vmatrix} S_{11} & S_{12} & S_{13} & 0 & 0 & 0 \\ S_{21} & S_{22} & S_{23} & 0 & 0 & 0 \\ S_{31} & S_{32} & S_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & S_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & S_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & S_{66} \end{vmatrix} \times \begin{vmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \tau_{23} \\ \tau_{13} \\ \tau_{12} \end{vmatrix}$$

or, in symbolic matrix notation

$$\underset{\sim}{\varepsilon} = \underset{\approx}{S}\underset{\sim}{\sigma}$$

where $\underset{\sim}{\varepsilon}$ stands for the 1x6 column vector of ε's and γ's; $\underset{\approx}{S}$ stands for the 6x6 array of the S_{ij}'s; and $\underset{\sim}{\sigma}$ stands for the 1x6 column vector of σ's and τ's.

The elements of the $\underset{\approx}{S}$ array are simply related to the Engineering constants by the relationships summarized at the top of Table I.

In the matrix format, the stress, $\underset{\sim}{\sigma}$, that would result from a general deformation, $\underset{\sim}{\varepsilon}$, is given by

$$\underset{\sim}{\sigma} = \underset{\approx}{C}\underset{\sim}{\varepsilon}$$

Consequently, the elastic constant array is the "inverse" (in a matrix sense) of $\underset{\approx}{S}$, viz,

$$\underset{\approx}{C} = \underset{\approx}{S}^{-1}$$

The relationship of the elements C_{ij} of the $\underset{\approx}{C}$ array to the Engineering constants are summarized in Table I.

Most theoretical treatments are formulated in terms of the elastic constants, $\underset{\approx}{C}$.

TABLE I

RELATIONSHIP BETWEEN ELASTIC CONSTANTS AND ENGINEERING CONSTANTS

Orthotropic materials

$$
\begin{array}{llll}
S_{11} = E_1^{-1} & S_{12} = -\nu_{12}E_1^{-1} & S_{13} = -\nu_{13}E_1^{-1} & S_{44} = G_{23}^{-1} \\
S_{12} = -\nu_{12}E_1^{-1} & S_{22} = E_2^{-1} & S_{23} = -\nu_{23}E_2^{-1} & S_{55} = G_{13}^{-1} \\
S_{13} = -\nu_{13}E_1^{-1} & S_{23} = -\nu_{23}E_2^{-1} & S_{33} = E_3^{-1} & S_{66} = G_{12}^{-1}
\end{array}
$$

$$\nu_{ij} = \nu_{ji}(E_j/E_i)$$

$$
\begin{array}{lll}
C_{11} = E_1[1 - (E_3/E_2)\nu_{23}^2]D & C_{22} = E_2[1 - (E_3/E_1)\nu_{13}^2]D & C_{44} = G_{23} \\
C_{12} = C_{21} = [E_2\nu_{12} + E_3\nu_{13}\nu_{23}]D & C_{23} = C_{32} = (E_3/E_1)[E_1\nu_{23} + E_2\nu_{12}\nu_{13}]D & C_{55} = G_{13} \\
C_{13} = C_{31} = E_3[\nu_{12}\nu_{23} + \nu_{13}]D & C_{33} = E_3[1 - (E_2/E_1)\nu_{12}^2]D & C_{66} = G_{12}
\end{array}
$$

$$D^{-1} = 1 - 2(E_3/E_1)\nu_{12}\nu_{23}\nu_{13} - \nu_{13}^2(E_3/E_1) - \nu_{23}^2(E_3/E_2) - \nu_{12}^2(E_2/E_1)$$

Transversely isotropic materials

"1" axis unique

$$E_L = E_1, \quad E_T = E_2 = E_3$$

$$\nu_A = \nu_{12} = \nu_{13}, \quad \nu_T = \nu_{23}$$

$$G_A = G_{12} = G_{13}, \quad G_T = G_{23} = E_T/[2(1 + \nu_T)]$$

"3" axis unique

$$E_L = E_3, \quad E_T = E_1 = E_2$$

$$\nu_A = \nu_{13} = \nu_{23}, \quad \nu_T = \nu_{12}$$

$$G_A = G_{13} = G_{23}, \quad G_T = G_{12} = E_T/[2(1 + \nu_T)]$$

Isotropic materials

$$E = E_1 = E_2 = E_3$$

$$\nu = \nu_{12} = \nu_{21} = \nu_{13} = \nu_{31} = \nu_{23} = \nu_{32}$$

$$G = G_{12} = G_{13} = G_{23} = E/[2(1 + \nu)]$$

(From: Anisotropic Elastic Behavior of Crystalline Polymers, R. L. McCullough, Treatise on Materials Science and Technology, 10B, p. 453-540, Academic Press, New York, 1977)

Additional symmetry of the material results in certain special conditions on the elastic constants, $\underset{\approx}{C}$ (as well as the compliance constants, $\underset{\approx}{S}$, and the engineering constants). Transversely, isotropic symmetry is of particular importance, fibers (e.g., graphite, Kevlar) frequently exhibit transversely isotropic response. Under conditions of transverse isotropy, the structure of the orthotropic array is preserved; however, certain special relationships between the material descriptors are imposed.

These relationships are summarized in Figure 2 and in Table I. Isotropic symmetry is exhibited by many (undrawn) polymer systems. Again, the structure of the orthotropic array is preserved with the special conditions $C_{11} = C_{22} = C_{33}$, and $C_{44} = C_{55} = C_{66} = \frac{1}{2}(C_{11}-C_{12})$. Consequently, no unique material axes exist for isotropic materials (i.e., the properties are the same in all directions). The results of the symmetry conditions for isotropic materials are summarized in Figure 2 and Table I.

These descriptions may be applied to describe the mechanical properties of the individual components of a sheet molding compound as well as the overall properties of the sheet molding material.

Orientation Dependence

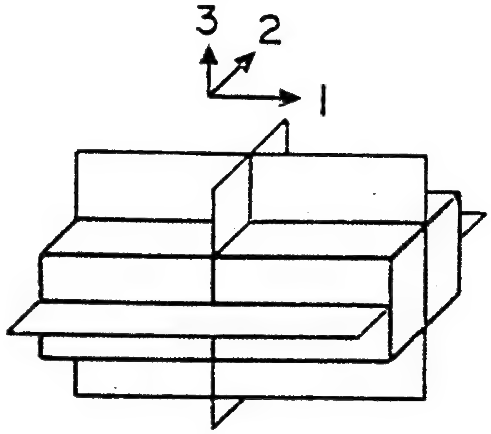
In the preceding discussion of the characterization of material descriptors, the simplifications resulting from material symmetry were emphasized by requiring that the unique axis associated with the symmetry class of the material were coincident with the loading (or deformation) directions imposed on the body of the material. This situation is rarely encountered. For example, fiber-reinforced laminates (e.g., tire plies) are frequently oriented at an angle of 45° with respect to the fiber direction. Fortunately, once the material system has been characterized along the unique axes, the material response in any arbitrary direction can be accurately predicted through the relationships summarized in Figure 3.

These relationships can be used to characterize the load-deformation response characteristics of a material $\bar{\underset{\approx}{A}}(\phi)$ at any arbitrary direction, ϕ, in terms of the associated descriptors associated with the symmetry axes of the material, $\underset{\approx}{A}$.

FIGURE 2

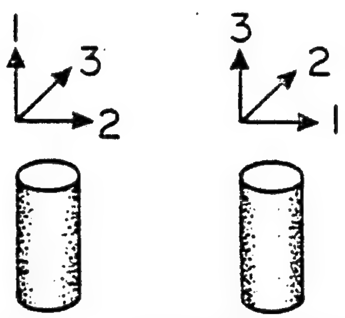
Components of the Elastic Constant Array for Materials with Orthotropic, Transversely Isotropic, and Isotropic Materials Symmetry

ORTHOTROPIC MATERIALS



$$\begin{pmatrix} \sigma_1 \\ \sigma_2 \\ \sigma_3 \\ \tau_{23} \\ \tau_{13} \\ \tau_{12} \end{pmatrix} = \begin{pmatrix} c_{11} & c_{12} & c_{13} & 0 & 0 & 0 \\ c_{12} & c_{22} & c_{23} & 0 & 0 & 0 \\ c_{13} & c_{23} & c_{33} & 0 & 0 & 0 \\ 0 & 0 & 0 & c_{44} & 0 & 0 \\ 0 & 0 & 0 & 0 & c_{55} & 0 \\ 0 & 0 & 0 & 0 & 0 & c_{66} \end{pmatrix} \begin{pmatrix} \epsilon_1 \\ \epsilon_2 \\ \epsilon_3 \\ \gamma_{23} \\ \gamma_{13} \\ \gamma_{12} \end{pmatrix}$$

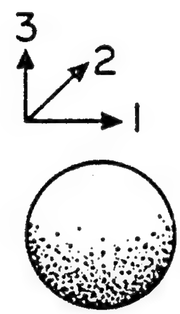
TRANSVERSLY ISOTROPIC MATERIALS



SPECIAL CONDITIONS

$c_{22} = c_{33}$	$c_{11} = c_{22}$
$c_{12} = c_{13}$	$c_{23} = c_{13}$
$c_{44} = \frac{1}{2}(c_{22} - c_{23})$	$c_{44} = c_{55}$
$c_{55} = c_{66}$	$c_{66} = \frac{1}{2}(c_{11} - c_{12})$

ISOTROPIC MATERIALS

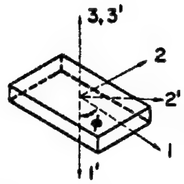


SPECIAL CONDITIONS

$c_{11} = c_{22} = c_{33}$

$c_{12} = c_{13} = c_{23}$

$c_{44} = c_{55} = c_{66} = \frac{1}{2}(c_{11} - c_{12})$



$$\Omega = \begin{pmatrix} \omega_{11} = \cos\phi & \omega_{12} = \sin\phi & \omega_{13} = 0 \\ \omega_{21} = -\sin\phi & \omega_{22} = \cos\phi & \omega_{23} = 0 \\ \omega_{31} = 0 & \omega_{32} = 0 & \omega_{33} = 1 \end{pmatrix}$$

$$\bar{A}_{11} = B_1 + B_7\cos 2\phi + B_8\cos 4\phi \qquad B_1 = \tfrac{1}{8}(3A_{11} + 3A_{22} + 2A_{12} + 4A_{66})$$
$$\bar{A}_{12} = \bar{A}_{21} = B_2 - B_8\cos 4\phi \qquad B_7 = \tfrac{1}{2}(A_{11} - A_{22})$$
$$\bar{A}_{16} = \bar{A}_{61} = \tfrac{1}{2}(B_7\sin 2\phi) + B_8\sin 4\phi \qquad B_8 = \tfrac{1}{8}(A_{11} + A_{22} - 2A_{12} - 4A_{66})$$
$$\bar{A}_{22} = B_1 - B_7\cos 2\phi + B_8\cos 4\phi \qquad B_2 = \tfrac{1}{8}(A_{11} + A_{22} + 6A_{12} - 4A_{66})$$
$$\bar{A}_{26} = \bar{A}_{62} = \tfrac{1}{2}(B_7\sin 2\phi) - B_8\sin 4\phi \qquad B_6 = \tfrac{1}{8}(A_{11} + A_{22} - 2A_{12} + 4A_{66})$$
$$\bar{A}_{66} = B_6 - B_8\cos 4\phi$$

Reduction in the transformation relationships for an orthotropic material in a state of plane stress or strain. The rotation transformation between the material axes ($\hat{e}_1, \hat{e}_2, \hat{e}_3$) and arbitrary load (or deformation) axes ($\hat{e}_1', \hat{e}_2', \hat{e}_3$) reduce to a simple rotation around the common $\hat{e}_3$ axis. Replacement of the A_{ij} by elastic constants C_{ij} yields expressions for the transformed elastic constants ($\bar{A}_{ij} = \bar{C}_{ij}$); replacement of the A_{ij} by the compliance constants S_{ij}, yields expressions for the transformed compliance constants ($\bar{A}_{ij} = \bar{S}_{ij}/m_i m_j$); $m_k = 1$ for $k = 1, 2,$ or 3; $m_k = 2$ for $k = 4, 5,$ or 6.

FIGURE 3

(From: Anisotropic Elastic Behavior of Crystalline Polymers, R. L. McCullough, ob. cit.)

MATERIALS MODELING

In this section, procedures will be developed for predicting the behavior of sheet molding materials comprised of short reinforcing fibers, particulate fillers, and a polymer phase. The approach proceeds by developing an aggregate model to account for orientation effects. The basic element of the aggregate model is taken to be an arbitrary "micro-region." The properties of the micro-region are subsequently predicted by associating the micro-region with a micro-laminate of aligned fibers. The combination of these results into a computational format for predicting the properties of sheet molding materials is summarized in the final section.

Aggregate Model

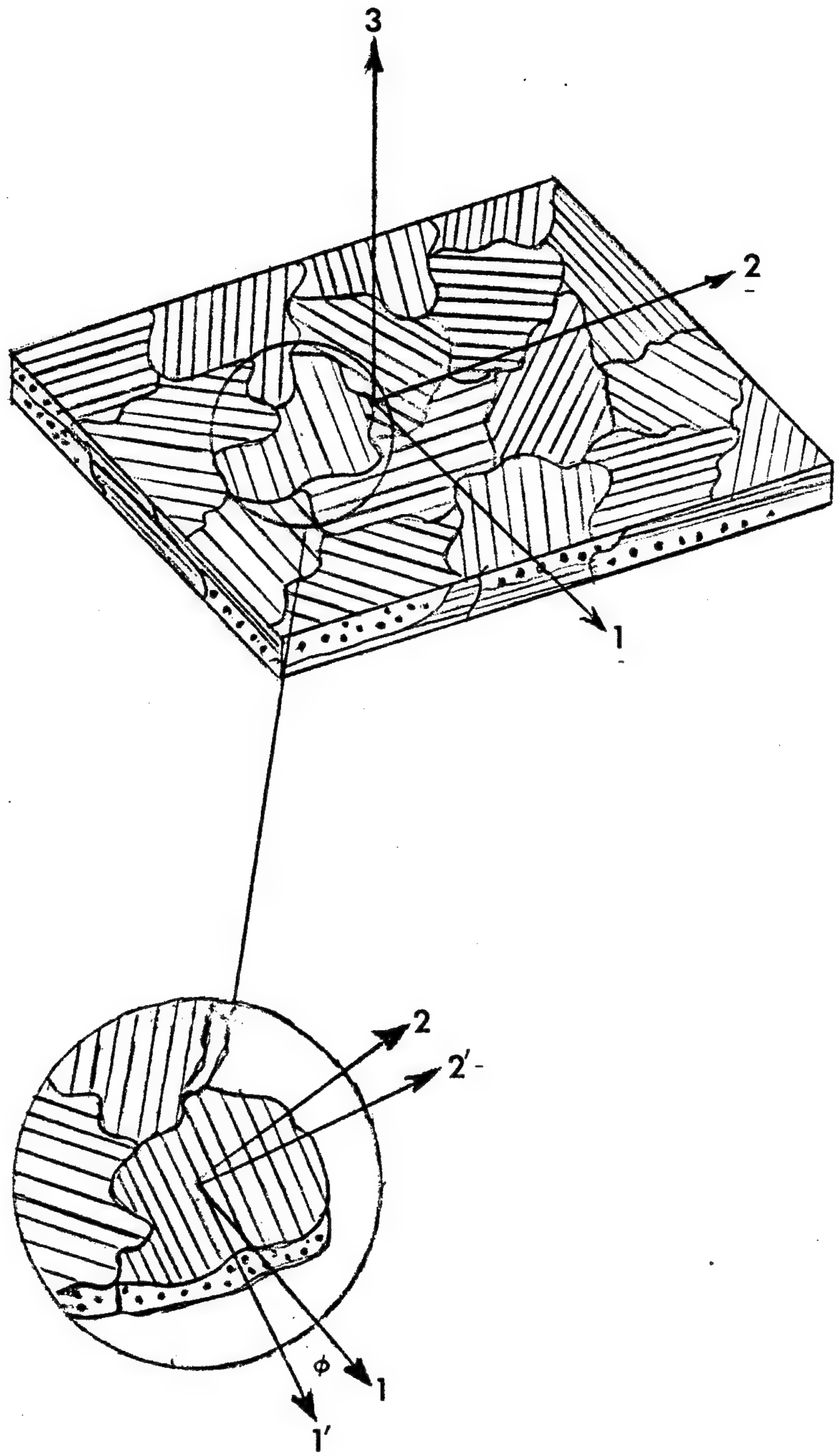
Under the Aggregate Model, a sheet molding material is viewed as partitioned into micro-regions as illustrated in Figure 4. As in the case of "grainy metals," each micro-region is treated as an apparent homogeneous (but anisotropic) material which may be described as an array of elastic constants, $\underset{\approx}{C}$. These micro-regions may assume a variety of orientations with respect to the external axes of the macroscopic body of material. Accordingly, the load-deformation characteristics along the "1", "2", and "3" axes of the bulk material are dependent upon the relative orientation of the unique "1'", "2'", "3'" material axes of the micro-region. Consequently, the transformations given in Figure 3 must be applied to each micro-region to obtain the appropriate contribution of the individual regions to the overall load-deformation response of the bulk material.

The fraction of micro-regions whose unique material axis "1'" makes an angle ϕ with respect to the external body axis "1" may be specified in terms of an orientation distribution function $n(\phi)$. This function gives the relative number of micro-regions whose unique axes are parallel and make an angle

FIGURE 4

Schematic Definition of
the Aggregate Model

AGGREGATE
MODEL



ϕ with respect to the external axis. Thus, if all the micro-regions were aligned along the body axis, $n(\phi=0) = 1$ and $n(\phi\neq 0) = 0$. Alternately, if the micro-regions were uniformly distributed in all directions, $n(\phi)$ = a constant for all values of ϕ.

It should be emphasized that the orientation function, $n(\phi)$, does not provide for an "out-of-plane tilting" of the micro-region. This type of orientation function is called a "Planar" distribution. Planar distributions are appropriate to sheet molding materials that are fabricated under conditions which maintain such planarity. Materials formed by injection molding may exhibit "out-of-plane tilting" and therefore will require a different form of an orientation distribution function.

The planar distribution function has the following important features:

$$n(\phi) = n(-\phi)$$

$$n(\phi) = n(+\phi)$$

$$\int_0^{\pi/2} n(\phi)\,d\phi = 1$$

The net contribution of the various micro-regions to the overall load-deformation response is given by averaging the relationships given in Figure 3 over the distribution; viz

$$\langle \underset{\approx}{A} \rangle = \int \bar{\underset{\approx}{A}}(\phi)\,n(\phi)\,d\phi \qquad \text{.... 1}$$

It is useful to introduce certain orientation parameters, "f" and "g" defined as

$$f = 2\,\langle \cos^2\phi \rangle - 1 \qquad \text{.... 2}$$

$$g = (1/5)(8\,\langle \cos^4\phi \rangle - 3) \qquad \text{.... 2b}$$

with

$$\langle \cos^m\phi \rangle = \int_0^{\pi/2} \cos^m\phi\, n(\phi)\,d\phi$$

These orientation parameters are constructed to provide a convenient scale for characterizing the state of orientation of a system. Thus, for $f = g = 0$, the micro-regions are randomly distributed within the "1-2" plane of the bulk material. For $f = g = 1$, the micro-regions are perfectly aligned along the "1" axis of the bulk material. Values of f and g between 0 and 1 represent intermediate states of orientation. These features of the planar orientation are summarized in Figure 5.

The results obtained by averaging under a planar orientation distributions are summarized in Table II in terms of the orientation parameters f and g. As before, the elastic constant array, $\underset{\approx}{C}$, and the compliance array, $\underset{\approx}{S}$, undergo the same transformations so that the results for orientation averaging can be generalized for an arbitrary material descriptor, $\langle\underset{\approx}{A}\rangle$ and base descriptor, $\underset{\approx}{A}$. Thus for $\underset{\approx}{A} \rightarrow \underset{\approx}{C}$, the relationships of Table II yield the orientation average of the elastic constant array; for $\underset{\approx}{A} \rightarrow \underset{\approx}{S}$, the orientation average of the compliance array is obtained. The factor B is introduced to account for the contraction of the compliance and elastic constants to second order tensors. For $\underset{\approx}{A} \rightarrow \underset{\approx}{C}$, $B = 1$; for $\underset{\approx}{A} \rightarrow \underset{\approx}{S}$, $B = 4$.

It can be shown that for reasonable forms for the planar orientation distribution (e.g., $n(\phi) = k\cos^b\phi$) that the orientation parameters f and g are related:

$$g = 2f(7-2f)/[5(4-2f)] \qquad \ldots.\ 3$$

so that only one parameter is required to describe the state of orientation. The orientation parameter, "f", is related to the "root-mean-square" orientation angle

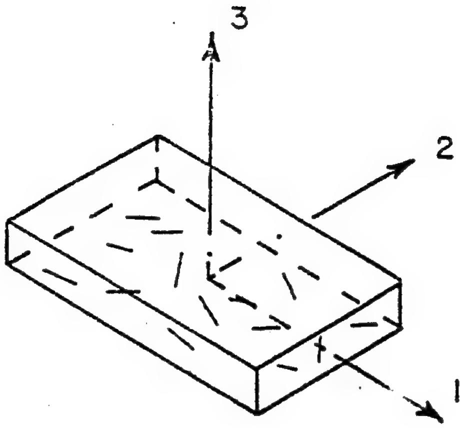
$$\phi_{rms} = \cos^{-1}\sqrt{(1+f)/2}\ .$$

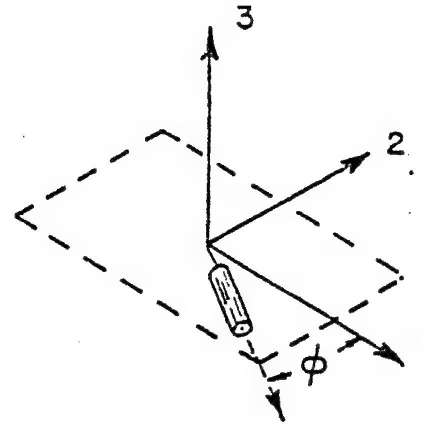
Hence for random distributions, $f = 0$ and $\phi_{rms} = 45°$. For perfect alignment, $f = 1$, and $\phi_{rms} = 0°$. For "slight" orientation, $f = 0.25$, $\phi_{rms} = 40°$; for "moderate" orientation,

FIGURE 5

Summary of the Features of a
Planar Orientation Distribution

Planar Orientation





$$n(\phi) = n(-\phi)$$

$$n(\phi) = n(\pi + \phi)$$

$$\int_0^{\pi/2} n(\phi)\, d\phi = 1$$

$$f_p = 2 \langle \cos^2 \phi \rangle - 1$$

$$g_p = \frac{1}{5} \left[8 \langle \cos^4 \phi \rangle - 3 \right]$$

$$\langle \cos^m \phi \rangle = \int_0^{\pi/2} n(\phi) \cos^m \phi \, d\phi$$

Aligned

$f_p = 1$

$g_p = 1$

Random

$f_p = 0$

$g_p = 0$

TABLE II

Averaged Properties of a
Planar Orientation Distribution

PLANAR ORIENTATION

$$\langle A_{11} \rangle = A^{o}_{11} - \left[a_{11} + \frac{5}{B} a_{66}\right] f \quad + \frac{5}{B} a_{66}\, g$$

$$\langle A_{12} \rangle = A^{o}_{12} + 4\, a_{12}\, f - 5\, a_{12}\, g$$

$$\langle A_{13} \rangle = A^{o}_{13} - a_{13}\, f$$

$$\langle A_{22} \rangle = A^{o}_{22} - \left[a_{22} + \frac{5}{B} a_{66}\right] f \quad + \frac{5}{B} a_{66}\, g$$

$$\langle A_{23} \rangle = A^{o}_{23} - a_{23}\, f$$

$$\langle A_{33} \rangle = A^{o}_{33}$$

$$\langle A_{44} \rangle = A^{o}_{44} - a_{44}\, f$$

$$\langle A_{55} \rangle = A^{o}_{55} - a_{55}\, f$$

$$\langle A_{66} \rangle = A^{o}_{66} + 4\, a_{66}\, f - 5\, a_{66}\, g$$

$$a_{ij} = A^{o}_{ij} - A_{ij}$$

$$A^{o}_{11} = A^{o}_{22} = k^{A} + \mu^{A}$$

$$A^{o}_{13} = A^{o}_{23} = \ell^{A}$$

$$A^{o}_{44} = A^{o}_{55} = B\gamma^{A}$$

$$A^{o}_{12} = k^{A} - \mu^{A}$$

$$A^{o}_{33} = n^{A}$$

$$A_{66} = B\mu^{A}$$

$$k^{A} = \frac{1}{4}\left[A_{11} + A_{22} + 2A_{12}\right]$$

$$\mu^{A} = \frac{1}{8}\left[A_{11} + A_{22} - 2A_{12} + \frac{4}{B} A_{66}\right]$$

$$\ell^{A} = \frac{1}{2}\left[A_{13} + A_{23}\right]$$

$$\gamma^{A} = \frac{1}{2B}\left[A_{44} + A_{55}\right]$$

$$n^{A} = A_{33}$$

$f = 0.5$, $\phi_{rms} = 30°$ while for "significant" orientation, $f = 0.75$, $\phi_{rms} = 20°$.

The aggregate model serves as a reasonable means of introducing relationships to account for the particular internal state of orientation of the representative micro-regions. The next task is to identify the nature of the arbitrary micro-regions and relate the properties of the micro-region, $\underset{\approx}{C}^*$, to the composition and fiber geometry of the sheet molding material.

Micro-Laminate Model

The preceding treatment of the aggregate model was based upon an arbitrary specification of a "micro-region." Indeed, the elements of the elastic constant array, $\underset{\approx}{C}$, that is used to describe the mechanical behavior of the micro-region could be treated as adjustable parameters for curve fitting. Since as many as nine independent parameters could be required, this empirical approach does not appear to be fruitful. In this section, the characteristic micro-region of the aggregate model is treated as a micro-laminate of perfectly aligned fibers. Accordingly, the domain of a micro-region is specified as that portion of the material that can be partitioned into volume elements in which the fibers within the region are all aligned parallel to an axis that makes an angle ϕ with the external body axis. The identification of such a region specifies the effective aspect ratio of the fiber. Thus for a sheet molding material (e.g., SMC-25) comprised of relatively long and straight collections of fibers, the aspect ratio would be large (e.g., $a > 250$). Alternately, for a sheet molding material in which the fiber bundles are "swirled" (e.g., SMC-65) such that arc length is relatively short, the effective aspect ratio could be as low as $a = 1 \rightarrow 10$.

Under this view of the micro-regions, the properties can be obtained from appropriate models for laminates. The general Wu-McCullough relationship can be specialized to this purpose.

The general relationship is of the form

$$\underset{\approx}{C}^* = \underset{\approx}{C}_o + (\underset{\approx}{M}^{-1} + \underset{\approx}{E}_o)^{-1} \qquad \ldots. \; 4$$

where $\underset{\approx}{C}^*$ is the 6x6 array of elastic constants for the microlaminate. The term $\underset{\approx}{C}_o$ is a 6x6 array of elastic constant for a "reference" material. The term $\underset{\approx}{E}_o$ is a 6x6 array which takes into account correlation effects. The elements of $\underset{\approx}{E}_o$ are dependent upon the aspect ratio, a, and certain elements of $\underset{\approx}{C}_o$. The elements of $\underset{\approx}{E}_o$ are summarized in Table III.

The quantity $\underset{\approx}{M}$ is a 6x6 array that is dependent upon the composition and the properties of the components compensated for correlation effects, viz,

$$\underset{\approx}{M} = \Sigma v_i \underset{\approx}{m}_i \qquad \ldots. \; 5$$

where v_i is the volume fraction of the i'th component; the term $\underset{\approx}{m}_i$ is a 6x6 array of the properties of component "i" compensated for correlations through the following relationships

$$\underset{\approx}{m}_i = (\underset{\approx}{R}_i^{-1} - \underset{\approx}{E}_o)^{-1} \qquad \ldots. \; 6a$$

$$\underset{\approx}{R}_i = \underset{\approx}{C}_i - \underset{\approx}{C}_o \qquad \ldots. \; 6b$$

The term $\underset{\approx}{C}_i$ is the 6x6 array of elastic constants for the i'th component

The versatility of the Wu-McCullough relationship is manifest through the term $\underset{\approx}{C}_o$. Assigning a reference material "zero" rigidity ($\underset{\approx}{C}_o = \underset{\approx}{0}$) yields the classic Reuss model; assigning the reference material an infinite rigidity ($\underset{\approx}{C}_o = \underset{\sim}{\infty}$) yields the Voigt model. If the reference material is taken as the resin phase ($\underset{\approx}{C}_o = \underset{\approx}{C}_{resin}$), the "best lower bounds" are obtained. If the fiber phase is selected as the reference phase ($\underset{\approx}{C}_o = \underset{\approx}{C}_{fiber}$), the "best upper bounds" are obtained. Usually, these bounds are too far apart to provide useful predictions. For the case, $\underset{\approx}{C}^* = \underset{\approx}{C}_o$, the "self-consistent" field models are obtained.

TABLE III

Elements of $\underset{\approx}{E}_o$

$$\underset{\approx}{E}_o = \begin{vmatrix} n & \ell & \ell & 0 & 0 & 0 \\ \ell & k+u & k-u & 0 & 0 & 0 \\ \ell & k-u & k+u & 0 & 0 & 0 \\ 0 & 0 & 0 & 4u & 0 & 0 \\ 0 & 0 & 0 & 0 & 4m & 0 \\ 0 & 0 & 0 & 0 & 0 & 4m \end{vmatrix}$$

$$n = 4\alpha h_5(a) - 4\beta h_2(a)$$

$$\ell = 2\alpha h_4(a)$$

$$k = \alpha h_3(a) - \beta h_1(a)$$

$$u = \tfrac{1}{2}\alpha h_3(a) - \beta h_1(a)$$

$$m = 2\alpha h_4(a) - \beta[\tfrac{1}{2}h_1(a) + h_2(a)]$$

$$\alpha = (C^o_{22} - C^o_{44})/(4C^o_{22}C^o_{44})$$

$$\beta = 1/(4C^o_{44})$$

$$h_2(a) = 1 - h_1(a)$$

$$h_4(a) = \tfrac{1}{2}[1 - h_3(a) - h_5(a)]$$

TABLE III (con't)

For $0 \leq a < 1$

$$y^2 = a^2/(1-a^2)$$

$$h_1(a) = y^2\{[(1/y) + y]\tan^{-1}(1/y) - 1\}$$

$$h_3(a) = y^4\{[(1+y^2)/2y^2] + 1\ [\tfrac{1}{2}(1/y)^3 - (1-y) - (3/2)y]\tan^{-1}(1/y)]\}$$

$$h_5(a) = (1+y^2)[(3-y^2)/(1+y^2) - (3/2)y\tan^{-1}(1/y))]$$

For $a = 1$

$$h_1(a) = 2/3$$

$$h_3(a) = 8/15$$

$$h_5(a) = 1/5$$

For $1 < a < \infty$

$$x^2 = (a^2-1)/a^2$$

$$Z = \{\ell n[(1+x)/(1-x)]\}/x$$

$$h_1(a) = [1 - \tfrac{1}{2}(1-x)Z]/x$$

$$h_3(a) = [(3/2) - \tfrac{1}{2} + \tfrac{1}{4}(x^2+2x-3)Z]/x^2$$

$$h_5(a) = [(1-x^2)/x^2]^2\{[(3-2x)/2(1-x)] - (3/4)Z)\}$$

It has been shown that the properties for a wide-range of fiber reinforced resin systems can be accurately predicted by assigning values to the $\underset{\approx}{C}_o$ array that correspond to a material (of equivalent composition and concentration) reinforced by spheres (aspect ratio = 1) rather than fibers. It was proposed that standard samples of glass bead reinforced resins be prepared and characterized over a range of volume fractions to provide the data necessary for constructing the $\underset{\approx}{C}_o$ array. These experimentally determined values for $\underset{\approx}{C}_o$ could be used in conjunction with Eq. 4 to predict the properties of fiber reinforced systems.

Recently, it was shown that the experimental determination of $\underset{\approx}{C}_o$ is not required. A model for particulate systems has been developed which accurately predicts the behavior of a wide variety of particulate filled systems over the sensible range ($v_p \leq 0.8$) of concentration of filler, v_p.

The "S-Mixing Rule" model for particulate systems is of the form

$$\underset{\approx}{S}_p = v_r \underset{\approx}{S}_{Lo} + v_p \underset{\approx}{S}_{Hi} + \tfrac{1}{2} v_r v_p (\underset{\approx}{S}_{Lo} - \underset{\approx}{S}_{Hi})$$

where v_r and v_p are the respective volume fractions of resin and filler particles. The quantity $\underset{\approx}{S}_{Lo} = \underset{\approx}{C}_{Lo}^{-1}$ where $\underset{\approx}{C}_{Lo}$ is obtained from Eq. 4 with $\underset{\approx}{C}_o = \underset{\approx}{C}_{resin}$ and the aspect ratio of the E_o term taken as a = 1. Similarly, the quantity $\underset{\approx}{S}_{Hi} = \underset{\approx}{C}_{Hi}^{-1}$ is obtained from Eq. 4 with $\underset{\approx}{C}_o = \underset{\approx}{C}_{filler}$ and a = 1. The relationships given in Table I are used to obtain the Young's modulus, Shear modulus, and Poisson's ratio from the computed values of $\underset{\approx}{S}_p$ for the particulate system.

The demonstrated success of the "S-Mixing Rule" provides a convenient means for generating the appropriate values for the parameters of the reference phase, $\underset{\approx}{C}_o$, as required by Eq. 4.

For a two-component fiber/resin system, the effective mechanical properties of the material may be predicted by the following procedures:

(i) For the current volume fraction of fiber and resin the appropriate values of $\underset{\approx}{C}_o$ are obtained by the application of the "S-mixing rule" (Eq. 5) for a system comprised of the equivalent volume fraction of resin and particles (a = 1) with the particles assigned the properties of the fiber.

(ii) The values obtained for $\underset{\approx}{C}_o$ are used in Eq. 4 along with the effective aspect ratio of the fiber to predict the properties of the micro-laminate, $\underset{\approx}{C}^*$.

(iii) The properties of the micro-laminate are subjected to the orientation averaging prescribed in Table II for a specified state of orientation, f.

(iv) The averaged values of $\underset{\approx}{C}$ for the sheet molding material are converted to the compliance array, $\underset{\approx}{S}$, and subsequently to the Engineering constants via the relationships given in Table I.

These procedures can be extended to resin/fiber/filler systems by introducing the notion of a "surrogate" matrix. In this approach, the resin and particulate filler system are viewed as a matrix phase. The properties of the matrix phase may be predicted by the application of the S-mixing rule for a particulate system with the apparent volume fractions of v_r' and v_p' for the resin and filler. These apparent volume fractions are related to the true volume fractions, v_r and v_p, through the relationships

$$v_r' = v_r/(v_r + v_p)$$

$$v_p' = v_p/(v_r + v_p)$$

so that $v_r' + v_p' = 1$.

The resulting properties for the isolated resin/filler systems are used to represent the behavior of a surrogate matrix material with properties $\underset{\approx}{C}_m$ as predicted by Eq. 5 with concentrations v_r' and v_p'. At this point, the computation

follows steps (i) through (iv) for a two-component fiber/matrix system with the computed values for the surrogate matrix assuming the role of the resin phase. The volume fraction of the surrogate matrix phase is given by $v_m = v_r + v_p = 1-v_f$, where v_f is the volume fraction of the fiber phase.

FORTRAN PROGRAM

Introduction

The preceding sections have been concerned with developing a model for predicting the Engineering properties of sheet molding compounds. These ideas have been implemented in the FORTRAN program SMC-3. Use of SMC-3 is described in this section. Two examples using SMC-3 and a program listing follow. Finally, a few cautions which need to be noted when implementing SMC-3 on a computing system other than the DEC-system 10 for which this version was written are discussed.

Examples and use of SMC-3 will be illustrated by specific examples. In general the execution of the program requires the following input data:

1) number of components
2) properties of constitutive phases
3) volume or weight fractions of components
4) effective aspect ratio of fibers
5) orientation of fibers

To facilitate the use of SMC-3, the Engineering constants (in psi) for polyester resin, E-glass fibers, and calcium carbonate filler have been stored internally in the program. If these properties are to be used, no data regarding the engineering properties of the constitutive phases need be entered. If the properties of one or all the phases are to be changed, this can be accomplished by the user during program execution. For an isotropic phase, e.g., resin, filler and some fibers, Young's modulus, the Shear modulus and Poisson's ratio will need to be entered. For transversely isotropic fibers (e.g., Kevlar) two Young's moduli, two Shear moduli and two Poisson's ratios will need to be entered. Example 1 demonstrates how properties for isotropic phases are changed. Example 2a shows how the properties are changed for a transversely isotropic fiber.

The composition can be entered either as volume fractions or weight fractions. If volume fractions are used, the data

are entered directly. Input using weight fractions also requires that the density of each phase must be entered. In examples 1 and 2, composition is input as weight and volume fractions, respectively.

The effective aspect ratio is entered directly upon request. The aspect ratio ranges from one to infinity. An aspect ratio of one corresponds to a spherical inclusion while an infinite aspect ratio corresponds to a continuous fiber.

Effect of fiber orientation on the Engineering constants can be investigated in either of two modes. First, the Engineering constants can be calculated for a single user selected fiber distribution. Orientation is specified by Herman's orientation function f. For random distribution f = 0. For perfectly aligned fibers f = 1.

Slightly oriented systems can be represented by "f" values in the range 0.2 to 0.3. Moderately oriented systems can be represented by "f" values of ~0.5. Significantly oriented systems can be represented by "f" values of 0.6 to 0.8

Second, a range of fiber orientations can be scanned. In this case the user specifies the initial and final values of the orientation parameter as well as the incremental step size.

For some input data it is possible to perform consistency checks. SMC-3 provides two such checks. The first is for composition fractions. If the fractions do not sum to unity, the user is instructed to re-enter the data.

The second consistency check is performed when one of the standard phases is replaced by an isotropic phase. In this case there are only two independent material descriptors, and it is possible to determine whether the input Young's modulus, Shear modulus and Poisson's ratio are self-consistent. The results of this check are as follows:

1) If input data are self-consistent, program execution continues.

2) If the input Poisson's ratio is inconsistent, an internally determined value is assigned and the user is informed of the change and asked for confirmation.

3) If the input Young's and Shear moduli require a negative Poisson's ratio or one larger than 0.5, the user is instructed to enter new moduli and Poisson's ratio.

Output from SMC-3 consists of two parts. The first is a summary of the input data. Included are the phase properties, composition as volume fractions, and the effective aspect ratio. Secondly, a tabular summary of the predicted material properties at specified orientations is printed. The table contains the predicted longitudinal, transverse, and perpendicular Young's moduli, the "1, 2", "1, 3" and "2, 3" Shear moduli and the "1, 2", "1, 3" and "2, 3" Poisson's ratios.

EXAMPLES

E X A M P L E 1

The purpose of this example is to illustrate the use of SMC3 for a three component system. The input data for the filler will be altered. An intentional error will be introduced to illustrate the operation of the self-consistancy check. After illustrating the checking feature, the data will be reset to the standard values.

☐ Data inputs by the user will be indicated by the symbol ✪.

☐ Comments are given in italics.

```
ENTER NUMBER OF COMPONENTS:
FOR RESIN/FIBER SYSTEM NUMB = 2
FOR RESIN/FIBER/FILLER SYSTEM NUMB = 3
```

✪ 3

```
TYPICAL PROPERTIES FOR A THREE COMPONENT
POLYESTER/E-GLASS/CALCIUM CARBONATE SYSTEM ARE:
```

	YOUNG'S MODULUS	SHEAR MODULUS	POISSON'S RATIO
RESIN	.5100E+06	.1960E+06	.301
FIBER	.1050E+08	.3940E+07	.333
FILLER	.6930E+07	.2620E+07	.323

```
IF THESE VALUES ARE ACCEPTABLE, ENTER A "0" (ZERO)
IF YOU WISH TO USE SIGNIFICANTLY DIFFERENT VALUES ENTER A "1" (ONE)
```

☐ *For illustrative purposes, the user elects to reduce the Young's Modulus of the filler from 6.93 X* 10^6 *to 4 X* 10^6 *while maintaining all other values for the properties. This will give inconsistant values for an isotropic material.*

✪ 1

```
IF RESIN  PROPERTIES ARE ACCEPTABLE ENTER A "0" (ZERO)
IF THEY ARE TO BE ALTERED ENTER A "1" (ONE)
```

✪ 0

```
    IF FIBER  PROPERTIES ARE ACCEPTABLE ENTER A "0" (ZERO)
    IF THEY ARE TO BE ALTERED ENTER A "1" (ONE)
0

    IF FILLER PROPERTIES ARE ACCEPTABLE ENTER A "0" (ZERO)
    IF THEY ARE TO BE ALTERED ENTER A "1" (ONE)
1

    ENTER YOUNG'S MODULUS FOR FILLER
4.E6

    ENTER SHEAR MODULUS FOR FILLER
2.62E6

    ENTER POISSON'S RATIO FOR FILLER
.323

    * * INPUT ERROR * *

    FOR INPUT VALUES OF THE YOUNG'S MODULUS AND SHEAR MODULUS
    POISSON'S RATIO WOULD BE NEGATIVE OR GREATER THAN 0.5

    RE-ENTER DATA
```

☐ *Return to standard values.*

```
    ENTER YOUNG'S MODULUS FOR FILLER
6.93E6

    ENTER SHEAR MODULUS FOR FILLER
.262E7

    ENTER POISSON'S RATIO FOR FILLER
.323

    THE CURRENT SET OF PROPERTIES FOR THE THREE
    COMPONENT SYSTEM ARE:
```

	YOUNG'S MODULUS	SHEAR MODULUS	POISSON'S RATIO
RESIN	.5100E+06	.1960E+06	.301
FIBER	.1050E+08	.3940E+07	.333
FILLER	.6930E+07	.2620E+07	.323

```
    IF THESE VALUES ARE ACCEPTABLE, ENTER A "0" (ZERO)
    IF YOU WISH TO USE SIGNIFICANTLY DIFFERENT VALUES ENTER A "1" (ONE)
0
```

□ *Weight fraction variables will be used. The use of weight fraction variables requires input for the density (or specific gravity) for each component.*

```
 IF THE COMPOSITION IS TO BE ENTERED AS VOLUME FRACTIONS,
 ENTER A "0" (ZERO)
 IF THE COMPOSITION IS TO BE ENTERED AS WEIGHT FRACTIONS,
 ENTER A "1" (ONE)
1

 WEIGHT FRACTION OF RESIN
.332

 DENSITY OF RESIN
1.2

 WEIGHT FRACTION OF FIBER
.25

 DENSITY OF FIBER
2.55

 WEIGHT FRACTION OF FILLER
.418

 DENSITY OF FILLER
2.40

 ENTER ASPECT RATIO OF THE FIBER
500.
```

□ *This value for an aspect ratio is associated with relatively long and straight fibers.*

```
THE STATE OF ORIENTATION OF THE FIBER IS SPECIFIED
BY THE HERMANS ORIENTATION FACTOR, F.
FOR PLANAR RANDOM F = 0
FOR PERFECTLY ALIGNED F = 1.

IF YOU WISH DATA FOR A SPECIFIED ORIENTATION ENTER A "0" (ZERO)
IF YOU WISH TO SCAN OVER A RANGE OF ORIENTATIONS ENTER A "1" (ONE)
0

ENTER SPECIFIC STATE OF ORIENTATION
0.
```

☐ *The input data is summarized for convenience and the predicted properties displayed for the various orientations.*

```
INPUT DATA
            YOUNG'S MODULUS    SHEAR MODULUS    POISSON'S RATIO
---------------------------------------------------------------
RESIN         .5100E+06          .1960E+06           .301
FIBER         .1050E+08          .3940E+07           .333
FILLER        .6930E+07          .2620E+07           .323

VOLUME FRACTIONS:
          RESIN    .504
          FIBER    .179
          FILLER   .317

ASPECT RATIO     500.0


CALCULATED DATA

ORIENTATION                           0.00
LONGITUDINAL YOUNG'S MODULUS        .2011E+07
TRANSVERSE YOUNG'S MODULUS          .2011E+07
PERPENDICULAR YOUNG'S MODULUS       .1615E+07
2,3 SHEAR MODULUS                   .6183E+06
1,3 SHEAR MODULUS                   .6183E+06
1,2 SHEAR MODULUS                   .7789E+06
1,2 POISSON'S RATIO                   .291
1,3 POISSON'S RATIO                   .287
2,3 POISSON'S RATIO                   .287

STOP

END OF EXECUTION
CPU TIME: 0.77  ELAPSED TIME: 3:15.28
EXIT
```

E X A M P L E 2a

The purpose of this example is to illustrate the use of SMC3 for a two component system. In this example, the fiber properties will be altered to reflect fiber anisotropy (e.g., KEVLAR 49).

☐ Data inputs by the user will be indicated by the symbol ✪.

☐ Comments are given in italics.

```
ENTER NUMBER OF COMPONENTS:
FOR RESIN/FIBER SYSTEM NUMB = 2
FOR RESIN/FIBER/FILLER SYSTEM NUMB = 3
✪2

TYPICAL PROPERTIES FOR A TWO COMPONENT
POLYESTER/E-GLASS FIBER SYSTEM ARE:
```

	YOUNG'S MODULUS	SHEAR MODULUS	POISSON'S RATIO
RESIN	.5100E+06	.1960E+06	.301
FIBER	.1050E+08	.3940E+07	.333

☐ *The stored values for the fiber properties are to be altered. The resin properties will be maintained.*

```
IF THESE VALUES ARE ACCEPTABLE, ENTER A "0" (ZERO)
IF YOU WISH TO USE SIGNIFICANTLY DIFFERENT VALUES ENTER A "1" (ONE)
✪1

IF RESIN  PROPERTIES ARE ACCEPTABLE ENTER A "0" (ZERO)
IF THEY ARE TO BE ALTERED ENTER A "1" (ONE)
✪0

IF FIBER  PROPERTIES ARE ACCEPTABLE ENTER A "0" (ZERO)
IF THEY ARE TO BE ALTERED ENTER A "1" (ONE)
✪1
```

```
IF FIBER IS ISOTROPIC ENTER A "0" (ZERO)
IF FIBER IS ANISOTROPIC (E.G. GRAPHITE) ENTER A "1" (ONE)
```

☐ *The fiber is transversely isotropic*

```
1

ENTER LONGITUDINAL YOUNG'S MODULUS
18.3E6

ENTER TRANSVERSE YOUNG'S MODULUS
1.83E6

ENTER SHEAR MODULUS, G12
6.88E6

ENTER SHEAR MODULUS, G23
.688E6

ENTER POISSON'S RATIO, POS12
.3

ENTER POISSON'S RATIO, POS23
.3
```

☐ *The new properties are displayed for verification by the user.*

```
THE CURRENT SET OF PROPERTIES FOR THE TWO
COMPONENT SYSTEM ARE:
```

	RESIN	FIBER
E1	.5100E+06	.1830E+08
E2	.5100E+06	.1830E+07
E3	.5100E+06	.1830E+07
G12	.1960E+06	.6880E+07
G13	.1960E+06	.6880E+07
G23	.1960E+06	.6880E+06
POS12	.301	.300
POS13	.301	.300
POS23	.301	.300

```
IF THESE VALUES ARE ACCEPTABLE, ENTER A "0" (ZERO)
IF YOU WISH TO USE SIGNIFICANTLY DIFFERENT VALUES ENTER A "1" (ONE)
0
```

```
IF THE COMPOSITION IS TO BE ENTERED AS VOLUME FRACTIONS,
ENTER A "0" (ZERO)
IF THE COMPOSITION IS TO BE ENTERED AS WEIGHT FRACTIONS,
ENTER A "1" (ONE)
0

VOLUME FRACTION RESIN
.53

VOLUME FRACTION FIBER
.47

ENTER ASPECT RATIO OF THE FIBER
2.
```

☐*This low value for the aspect ratio is associated with pronounced fiber curvature and/or very short fiber lengths.*

```
THE STATE OF ORIENTATION OF THE FIBER IS SPECIFIED
BY THE HERMANS ORIENTATION FACTOR, F.
FOR PLANAR RANDOM F = 0
FOR PERFECTLY ALIGNED F = 1.

IF YOU WISH DATA FOR A SPECIFIED ORIENTATION ENTER A "0" (ZERO)
IF YOU WISH TO SCAN OVER A RANGE OF ORIENTATIONS ENTER A "1" (ONE)
```

☐*The user elects to scan over the possible range of orientation.*

```
1

ENTER THE STARTING VALUE FOR "F"
0.

ENTER THE FINAL VALUE FOR "F"
1.

ENTER THE INCREMENTS FOR STEPPING VALUES OF "F"
.25
```

☐ *The input data is summarized for convenience and the predicted properties displayed for the various orientations.*

INPUT DATA

	RESIN	FIBER
E1	.5100E+06	.1830E+08
E2	.5100E+06	.1830E+07
E3	.5100E+06	.1830E+07
G12	.1960E+06	.6880E+07
G13	.1960E+06	.6880E+07
G23	.1960E+06	.6880E+06
POS12	.301	.300
POS13	.301	.300
POS23	.301	.300

VOLUME FRACTIONS:

RESIN	.530
FIBER	.470

ASPECT RATIO 2.0

CALCULATED DATA

ORIENTATION	0.00
LONGITUDINAL YOUNG'S MODULUS	.3065E+07
TRANSVERSE YOUNG'S MODULUS	.3065E+07
PERPENDICULAR YOUNG'S MODULUS	.1158E+07
2,3 SHEAR MODULUS	.8269E+06
1,3 SHEAR MODULUS	.8269E+06
1,2 SHEAR MODULUS	.1300E+07
1,2 POISSON'S RATIO	.178
1,3 POISSON'S RATIO	.439
2,3 POISSON'S RATIO	.439

ORIENTATION	0.25
LONGITUDINAL YOUNG'S MODULUS	.3547E+07
TRANSVERSE YOUNG'S MODULUS	.2563E+07
PERPENDICULAR YOUNG'S MODULUS	.1155E+07
2,3 SHEAR MODULUS	.7211E+06
1,3 SHEAR MODULUS	.9327E+06
1,2 SHEAR MODULUS	.1304E+07
1,2 POISSON'S RATIO	.215
1,3 POISSON'S RATIO	.455
2,3 POISSON'S RATIO	.418

```
ORIENTATION                          0.50
LONGITUDINAL YOUNG'S MODULUS       .4027E+07
TRANSVERSE YOUNG'S MODULUS         .2065E+07
PERPENDICULAR YOUNG'S MODULUS      .1149E+07
2,3 SHEAR MODULUS                  .6152E+06
1,3 SHEAR MODULUS                  .1039E+07
1,2 SHEAR MODULUS                  .1300E+07
1,2 POISSON'S RATIO                  .266
1,3 POISSON'S RATIO                  .466
2,3 POISSON'S RATIO                  .395


ORIENTATION                          0.75
LONGITUDINAL YOUNG'S MODULUS       .4505E+07
TRANSVERSE YOUNG'S MODULUS         .1576E+07
PERPENDICULAR YOUNG'S MODULUS      .1135E+07
2,3 SHEAR MODULUS                  .5094E+06
1,3 SHEAR MODULUS                  .1144E+07
1,2 SHEAR MODULUS                  .1285E+07
1,2 POISSON'S RATIO                  .341
1,3 POISSON'S RATIO                  .470
2,3 POISSON'S RATIO                  .373


ORIENTATION                          1.00
LONGITUDINAL YOUNG'S MODULUS       .4987E+07
TRANSVERSE YOUNG'S MODULUS         .1107E+07
PERPENDICULAR YOUNG'S MODULUS      .1107E+07
2,3 SHEAR MODULUS                  .4036E+06
1,3 SHEAR MODULUS                  .1250E+07
1,2 SHEAR MODULUS                  .1250E+07
1,2 POISSON'S RATIO                  .459
1,3 POISSON'S RATIO                  .459
2,3 POISSON'S RATIO                  .352

STOP

END OF EXECUTION
CPU TIME: 0.99  ELAPSED TIME: 3:52.92
EXIT
```

E X A M P L E   2b

The purpose of this example is to illustrate the use of SMC3 to obtain the properties of a two component uni-directional laminate of continuous glass fibers. In this example, stored properties will be used.

- Data input by the user will be indicated by the symbol ✪.
- Comments are given in italics.

```
ENTER NUMBER OF COMPONENTS:
FOR RESIN/FIBER SYSTEM NUMB = 2
FOR RESIN/FIBER/FILLER SYSTEM NUMB = 3
✪2

TYPICAL PROPERTIES FOR A TWO COMPONENT
POLYESTER/E-GLASS FIBER SYSTEM ARE:

              YOUNG'S MODULUS    SHEAR MODULUS    POISSON'S RATIO
-----------------------------------------------------------------
RESIN           .5100E+06          .1960E+06          .301
FIBER           .1050E+08          .3940E+07          .333


IF THESE VALUES ARE ACCEPTABLE, ENTER A "0" (ZERO)
IF YOU WISH TO USE SIGNIFICANTLY DIFFERENT VALUES ENTER A "1" (ONE)
✪0


IF THE COMPOSITION IS TO BE ENTERED AS VOLUME FRACTIONS,
ENTER A "0" (ZERO)
IF THE COMPOSITION IS TO BE ENTERED AS WEIGHT FRACTIONS,
ENTER A "1" (ONE)
✪0

VOLUME FRACTION RESIN
✪.6

VOLUME FRACTION FIBER
✪.4
```

```
ENTER ASPECT RATIO OF THE FIBER
1000000.
```

The value of 1000000 for the aspect ratio is used to represent a continuous fiber.

```
THE STATE OF ORIENTATION OF THE FIBER IS SPECIFIED
BY THE HERMANS ORIENTATION FACTOR, F.
FOR PLANAR RANDOM F = 0
FOR PERFECTLY ALIGNED F = 1.
```

Since the properties of a unidirectional laminate are desired, the orientation factor is set at unity to represent aligned fibers.

```
IF YOU WISH DATA FOR A SPECIFIED ORIENTATION ENTER A "0" (ZERO)
IF YOU WISH TO SCAN OVER A RANGE OF ORIENTATIONS ENTER A "1" (ONE)
0

ENTER SPECIFIC STATE OF ORIENTATION
1.
```

The input data is summarized for convenience and the predicted properties displayed. (Note that the "star field" for the aspect ratio indicates a continuous fiber with an infinite aspect ratio.)

INPUT DATA

	YOUNG'S MODULUS	SHEAR MODULUS	POISSON'S RATIO
RESIN	.5100E+06	.1960E+06	.301
FIBER	.1050E+08	.3940E+07	.333

```
VOLUME FRACTIONS:
          RESIN    .600
          FIBER    .400

ASPECT RATIO   *******
```

CALCULATED DATA

ORIENTATION	1.00
LONGITUDINAL YOUNG'S MODULUS	.4506E+07
TRANSVERSE YOUNG'S MODULUS	.1249E+07
PERPENDICULAR YOUNG'S MODULUS	.1249E+07
2,3 SHEAR MODULUS	.4574E+06
1,3 SHEAR MODULUS	.5589E+06
1,2 SHEAR MODULUS	.5589E+06
1,2 POISSON'S RATIO	.319
1,3 POISSON'S RATIO	.319
2,3 POISSON'S RATIO	.365

STOP

END OF EXECUTION
CPU TIME: 0.54 ELAPSED TIME: 1:19.02

CALCULATED DATA

ORIENTATION	1.00
LONGITUDINAL YOUNG'S MODULUS	.4506E+07
TRANSVERSE YOUNG'S MODULUS	.1249E+07
PERPENDICULAR YOUNG'S MODULUS	.1249E+07
2,3 SHEAR MODULUS	.4574E+06
1,3 SHEAR MODULUS	.5589E+06
1,2 SHEAR MODULUS	.5589E+06
1,2 POISSON'S RATIO	.319
1,3 POISSON'S RATIO	.319
2,3 POISSON'S RATIO	.365

STOP

END OF EXECUTION
CPU TIME: 0.54 ELAPSED TIME: 1:19.02

FORTRAN Listing

Internal documentation for SMC-3 is provided by "Comment" statements to define variables, specify operations, and indicate program flow at the appropriate locations.

```
C                        ------------
C                        PROGRAM SMC-3
C                        ------------
C
C       THIS PROGRAM WRITTEN BY:
C
C       DR. R. L. MCCULLOUGH
C       UNIVERSITY OF DELAWARE
C       NEWARK, DELAWARE
C
C       STUART MCGEE
C       UNIVERSITY OF DELAWARE
C       NEWARK, DELAWARE
C
C       JUNE 4, 1979  (LAST REVISION)
C
C* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
C
C         THIS PROGRAM USES THE WU-MCCULLOUGH RELATIONSHIP IN
C       CONJUNCTION WITH THE AGGREGATE MODEL TO PREDICT PROPERTIES
C       FOR TWO COMPONENT (RESIN/FIBER) OR THREE COMPONENT
C       (RESIN/FIBER/FILLER) SHEET MOLDING COMPOUNDS.
C
C* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
C
C                       MATERIAL SPECIFICATION
C
C         THE MINIMUM DATA REQUIRED FOR THE EXECUTION OF THE
C       PROGRAM IS:
C
C         V2(K) THE VOLUME FRACTION OF PHASE K (K=1,RESIN,
C               K=2,FIBER, K=3,FILLER)
C         AA2   THE EFFECTIVE ASPECT RATIO OF THE FIBER
C         F     THE STATE OF ORIENTATION OF THE FIBERS
C
```

```
C           STANDARD VALUES FOR THE YOUNG'S MODULUS, SHEAR MODULUS,
C         AND POISSON'S RATIO FOR POLYESTER RESIN, E-GLASS FIBERS,
C         AND CALCIUM CARBONATE FILLER ARE STORED INTERNALLY.
C         THESE VALUES MAY BE ALTERED UNDER CONTROL OF THE USER
C         DURING EXECUTION OF THE PROGRAM.  PROVISION IS MADE TO
C         ACCEPT WEIGHT FRACTION VARIABLES IN LIEU OF VOLUME
C         FRACTION VARIABLES.  THE USE OF WEIGHT FRACTION
C         VARIABLES REQUIRES INPUT FOR THE DENSTIY OF EACH
C         COMPONENT.
C
C* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
C
C                          PROGRAM SUBROUTINES
C
C           THE PROGRAM IS SEGMENTED UNDER THE FOLLOWING SUB-
C         ROUTINES:
C
C         INPUT    THIS SUBROUTINE PROVIDES AN INTERACTIVE MODE FOR
C                  DATA ACQUISITION.  CONSISTENCY CHECKS ARE
C                  PROVIDED ON VOLUME FRACTION (OR WEIGHT FRACTION)
C                  VARIABLES.
C
C                  CALLS:  ALTER, PRINT1, PRINT2
C
C         ALTER    THIS SUBROUTINE PROVIDES FOR REPLACING ANYONE
C                  OR ALL OF THE STORED VALUES FOR THE PROPERTIES
C                  OF THE RESIN, FIBER, AND/OR FILLER PHASE WITH A
C                  SET SELECTED BY THE USER.  ALTERED VALUES OF
C                  YOUNG'S MODULUS, SHEAR MODULUS AND POISSON'S
C                  RATIO ARE CHECKED FOR CONSISTENCY WHEN THE
C                  INTPUT IS FOR AN ISOTROPIC MATERIAL.
C
C                  CALLS:  CHECK
C
C         CHECK    THIS SUBROUTINE CHECKS ALTERED VALUES OF YOUNG'S
```

```
      DIMENSION RESIN(6,6),FIBER(6,6),FILLER(6,6),CZERO(6,6)
      COMMON /B1/ NREAD,NWRITE
      COMMON /B3/ E1(3),E2(3),E3(3),G12(3),G13(3),G23(3),POS12(3),
     CPOS13(3),POS23(3),V2(3),AA2,FSTART,FSTOP,FADD
C---THE FOLLOWING DATA FILES CONTAIN THE TYPICAL VALUES FOR
C-- THE PROPERTIES OF THE COMPONENTS IN THE ORDER RESIN/FIBER/
C-- FILLER
      DATA E1/.51E6,.105E8,.693E7/,G12/.196E6,.394E7,.262E7/
      DATA E2/.51E6,.105E8,.693E7/,G13/.196E6,.394E7,.262E7/
      DATA E3/.51E6,.105E8,.693E7/,G23/.196E6,.394E7,.262E7/
      DATA POS12/.301,.333,.323/,POS13/.301,.333,.323/
      DATA POS23/.301,.33,.323/,ISO/0/
C---DATA FILE FOR OUTPUT TALBES AND DEVICE NUMBERS FOR INPUT
C-- (NREAD) AND FOR OUTPUT (NWRITE)
      DATA PHASE/5HRESIN,5HFIBER,5HFILLE,2*1H ,1HR/
      DATA NREAD,NWRITE/5,5/
C---CALL ON THE SUBROUTINE INPUT TO ENTER THE DATA INTO THE
C-- PROGRAM
C---ALL MAJOR VARIABLES ARE TRANSFERED THROUGH COMMON BLOCKS
      CALL INPUT(NUMB,ISO)
C---PRINT A SUMMARY OF THE INPUT DATA
      WRITE(NWRITE,10)
   10 FORMAT(//2X,10HINPUT DATA)
      IF(ISO .EQ. 0) CALL PRINT1(NUMB)
      IF(ISO .EQ. 1) CALL PRINT2(NUMB)
      WRITE(NWRITE,20) (PHASE(I),PHASE(I+3),V2(I),I=1,NUMB)
   20 FORMAT(/2X,17HVOLUME FRACTIONS:/(12X,A5,A1,1X,F5.3))
      WRITE(NWRITE,30) AA2
   30 FORMAT(/2X,12HASPECT RATIO,2X,F7.1)
C---CONVERT ENGINEERING CONSTANTS TO ELASTIC CONSTANTS
      CALL ELAST(1,RESIN)
      CALL ELAST(2,FIBER)
      CALL ELAST(3,FILLER)
C---CONSTRUCT SURROGATE MATRIX PHASE WHICH HAS THE PROPERTIES
C-- OF THE RESIN/FILLER SYSTEM
```

```
      CALL AMATIN(AAA,TRANS,NDUM)
      DO 80 K=1,6
      DO 80 J=1,6
       CSTAR(K,J)=CZERO(K,J)+TRANS(K,J)
C---CSTAR IS THE ELASTIC CONSTANT ARRAY FOR THE MICROLAMINATE
   80 CONTINUE
      WRITE(NWRITE,90)
   90 FORMAT(//2X,15HCALCULATED DATA)
      DO 120 L=1,50
      F=FSTART+FADD*FLOAT(L-1)
      IF(F .GT. FSTOP) GO TO 130
C---COMPUTE ORIENTATION AVERAGE OF AN AGGREGATE OF MICRO-
C-- LAMINATES
      CALL PLANAR(1.,F,CSTAR,TRANS)
      CALL AMATIN(TRANS,S,NDUM)
C---CONVERT TO ENGINEERING CONSTANTS
       DO 100 K=1,6
        EC(K)=1./S(K,K)
  100  CONTINUE
       EC(7)=- EC(1)*S(1,2)
       EC(8)=- EC(1)*S(1,3)
       EC(9)=- EC(2)*S(2,3)
C---PRINT THE CALCULATED DATA
      WRITE(NWRITE,110) F,(EC(J),J=1,9)
  110 FORMAT(/2X,11HORIENTATION,24X,F5.2/2X,12HLONGITUDINAL,
     C1X,15HYOUNG'S MODULUS,4X,E10.4/2X,10HTRANSVERSE,1X
     C15HYOUNG'S MODULUS,6X,E10.4/2X,13HPERPENDICULAR,1X
     C15HYOUNG'S MODULUS,3X,E10.4/2X,17H2,3 SHEAR MODULUS,15X
     CE10.4/2X,17H1,3 SHEAR MODULUS,15X,E10.4/2X,3H1,2,1X,
     C13HSHEAR MODULUS,15X,E10.4/2X,13H1,2 POISSON'S,1X
     C5HRATIO,16X,F5.3/2X,19H1,3 POISSON'S RATIO,16X,F5.3/
     C2X,19H2,3 POISSON'S RATIO,16X,F5.3/)
  120 CONTINUE
  130 STOP
      END
```

```
C                    MODULUS, SHEAR MODULUS, AND POISSON'S RATIO
C                    FOR SELF-CONSISTENCY
C
C          PRINT1    THIS ROUTINE IS USED TO PRINT THE PROPERTY
C                    DATA FOR ISOTROPIC MATERIALS.
C
C          PRINT2    THIS ROUTINE IS USED TO PRINT THE PROPERTY
C                    DATA FOR ANISOTROPIC MATERIALS.
C
C          ELAST     THIS SUBROUTINE CONVERTS ENGINEERING CONSTANTS
C                    (YOUNG'S MODULUS, SHEAR MODULUS, AND POISSON'S
C                    RATIO) INTO THE 6X6 ARRAY OF ELASTIC CONSTANTS,
C                    "C(K)", FOR THE K'TH PHASE COMPONENT.
C
C          SMIX      THIS SUBROUTINE IS USED TO GENERATE PROPERTIES
C                    FOR THE SPECIAL CASE OF PARTICULATE SYSTEMS.
C                    (THE ASPECT RATIO IS SET TO 1.)
C
C                    CALLS:  EMAKE,COMP,AMATIN
C
C          COMP      THIS SUBROUTINE COMPENSATES THE PROPERTIES OF
C                    EACH PHASE COMPONENT FOR CORRELATION EFFECTS.
C
C                    CALLS:  AMATIN
C
C          AMATIN    A SPECIAL MATRIX INVERSION ROUTINE WHICH
C                    MAKES USE OF SYMMETRY FOR MORE EFFICIENT
C                    INVERSIONS.
C
C          PLANAR    THIS SUBROUTINE GENERATES THE AVERAGE PROPERTIES
C                    OF A SYSTEM IN THE STATE OF PLANAR ORIENTATION
C                    CHARACTERIZED BY THE ORIENTATION FACTOR, F.
C
         DIMENSION CM(6,6),EZERO(6,6),BIGM(6,6),TRANS(6,6),CSTAR(6,6)
         DIMENSION AAA(6,6),S(6,6),EC(9),NDUM(4),PHASE(6)
```

```
      VS=V2(1)+V2(3)
      VHI=V2(3)/VS
C---VHI IS THE APPARENT VOLUME FRACTION OF FILLER IF NO FIBER
C-- WERE PRESENT
      CALL SMIX(VHI,RESIN,FILLER,CM)
C---CM IS THE 6X6 ELASTIC CONSTANT ARRAY FOR THE SURROGATE
C-- MATRIX PHASE
C---COMPUTE REFERENCE PHASE CZERO
      VX=V2(2)
      CALL SMIX(VX,CM,FIBER,CZERO)
C---COMPUTE PROPERTIES OF MICROLAMINATE FROM
C--     CSTAR = CZERO + (BIGM**-1 + EZERO)**-1
      CALL EMAKE(EZERO,CZERO,AA2)
      DO 40 K=1,6
      DO 40 J=1,6
       BIGM(K,J)=0.
   40 CONTINUE
C---COMPUTE COMPENSATED PROPERTIES OF SURROGATE MATRIX
      CALL COMP(CZERO,CM,EZERO,TRANS)
      DO 50 K=1,6
      DO 50 J=1,6
       BIGM(K,J)=BIGM(K,J)+(1.-VX)*TRANS(K,J)
   50 CONTINUE
C---COMPUTE COMPENSATED PROPENTIES OF FIBER PHASE
      CALL COMP(CZERO,FIBER,EZERO,TRANS)
      DO 60 K=1,6
      DO 60 J=1,6
       BIGM(K,J)=BIGM(K,J)+VX*TRANS(K,J)
   60 CONTINUE
C---TRANS IS THE INVERSE OF BIGM
      CALL AMATIN(BIGM,TRANS,NDUM)
      DO 70 K=1,6
      DO 70 J=1,6
       AAA(K,J)=TRANS(K,J)+EZERO(K,J)
   70 CONTINUE
```

```
C* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
      SUBROUTINE INPUT(NUMB,ISO)
C
C       THIS SUBROUTINE IS AN INTERACTIVE ROUTINE FOR OBTAINING
C     INPUT DATA.
C
C       TYPICAL PROPERTIES FOR POLYESTER RESIN, E-GLASS FIBERS
C     AND CALCIUM CARBONATE FILLER ARE STORED INTERNALLY.
C     THESE VALUES CAN BE ALTERED BY THE USER DURING PROGRAM
C     EXECUTION.  THE ALTERED VALUES WILL BE CHECKED FOR
C     SELF-CONSISTENCY.
C
C       PHASE CONCENTRATIONS MAY BE ENTERED EITHER AS VOLUME
C     OR WEIGHT FRACTIONS.  CONCENTRATIONS ENTERED AS WEIGHT
C     FRACTIONS WILL BE CONVERTED INTERNALLY TO VOLUME
C     FRACTIONS.  BOTH VOLUME AND WEIGHT FRACTION VARIABLES
C     WILL BE TESTED FOR CONSISTENCY.
C
C       THE EFFECTIVE ASPECT RATIO IS ENTERED AS A UNITLESS
C     QUANTITY IN THE RANGE OF 0. TO 100,000.  THE ASPECT
C     RATIO OF A SPHERICAL INCLUSION IS 1.
C
C       THE STATE OF ORIENTATION IS SPECIFIED BY THE HERMANS
C     ORIENTATION FACTOR "F".  PROVISIONS ARE AVAILABLE
C     TO ACCEPT A SINGLE VALUE FOR "F" OR TO CONDUCT
C     A SCAN FROM 0 (RANDOM) TO 1 (PERFECT ALIGNMENT) IN
C     SPECIFIED STEPS.
C
C       ROUTINES CALLED:
C             ALTER
C             PRINT1
C             PRINT2
C
      COMMON /B1/ NREAD,NWRITE
      COMMON /B3/ E1(3),E2(3),E3(3),G12(3),G13(3),G23(3),POS12(3),
```

```
     CPOS13(3),POS23(3),V2(3),AA2,FSTART,FSTOP,FADD
      DIMENSION PHASE(6),DELT(3),DEN(3),DX(3)
C---SET HEADINGS FOR OUTPUT TABLES
      DATA PHASE/5HRESIN,5HFIBER,5HFILLE,2*1H ,1HR/
C---ENTER NUMBER OF COMPONENTS (NUMB)
      WRITE(NWRITE,10)
   10 FORMAT(2X,27HENTER NUMBER OF COMPONENTS:/2X,9HFOR RESIN
     C22H/FIBER SYSTEM NUMB = 2/2X,22HFOR RESIN/FIBER/FILLER,1X
     C15HSYSTEM NUMB = 3)
   20 READ(NREAD,30) NUMB
   30 FORMAT(I1)
      IF(NUMB .EQ. 2 .OR. NUMB .EQ. 3) GO TO 50
      WRITE(NWRITE,40)
   40 FORMAT(2X,19H* * INPUT ERROR * *//2X,16HRE-ENTER NUMBER
     C13HOF COMPONENTS  )
      GO TO 20
C---PRINT THE STANDARD PROPERTIES FOR THE PROPER SYSTEM
   50 IF(NUMB .EQ. 2) WRITE(NWRITE,60)
      IF(NUMB .EQ. 3) WRITE(NWRITE,70)
   60 FORMAT(2X,38HTYPICAL PROPERTIES FOR A TWO COMPONENT/
     C2X,35HPOLYESTER/E-GLASS FIBER SYSTEM ARE:  //)
   70 FORMAT(2X,40HTYPICAL PROPERTIES FOR A THREE COMPONENT  /
     C2X47HPOLYESTER/E-GLASS/CALCIUM CARBONATE SYSTEM ARE:  //)
      CALL PRINT1(NUMB)
C---CHECK TO SEE IF THESE ARE ACCEPTABLE VALUES
      WRITE(NWRITE,80)
   80 FORMAT(//2X,44HIF THESE VALUES ARE ACCEPTABLE, ENTER A "0"
     C6H(ZERO)/2X,43HIF YOU WISH TO USE SIGNIFICANTLY DIFFERENT
     C24HVALUES ENTER A "1" (ONE)  )
      READ (5,30) MALTER
      IF(MALTER .EQ. 0) GO TO 120
   90 CALL ALTER(NUMB,ISO)
C---PRINT THE ALTERED PROPERTIES FOR THE BENEFIT OF THE USER
      IF(NUMB .EQ. 2) WRITE(NWRITE,100)
  100 FORMAT(2X,42HTHE CURRENT SET OF PROPERTIES FOR THE TWO  /
```

```
     C2X,21HCOMPONENT SYSTEM ARE:  //)
      IF(NUMB .EQ. 3) WRITE(NWRITE,110)
  110 FORMAT(2X,44HTHE CURRENT SET OF PROPERTIES FOR THE THREE /
     C2X,21HCOMPONENT SYSTEM ARE:  //)
      IF(ISO .EQ. 0) CALL PRINT1(NUMB)
      IF(ISO .EQ. 1) CALL PRINT2(NUMB)
      WRITE(NWRITE,80)
      READ(NREAD,30) MALTER
      IF(MALTER .EQ. 1) GO TO 90
C---DETERMINE HOW COMPOSITION IS TO BE ENTERED
  120 WRITE(NWRITE,130)
  130 FORMAT(//2X,45HIF THE COMPOSITION IS TO BE ENTERED AS VOLUME
     C11H FRACTIONS,/2X,18HENTER A "0" (ZERO)/2X,7HIF THE
     C49HCOMPOSITION IS TO BE ENTERED AS WEIGHT FRACTIONS,
     C/2X,17HENTER A "1" (ONE)  )
      READ(NREAD,30) MCOMP
      IF(MCOMP .EQ. 1) GO TO 180
C---ENTER COMPOSITION AS VOLUME FRACTIONS
  140 TEST=0.
      DO 160 K=1,NUMB
      WRITE(NWRITE,150) PHASE(K),PHASE(K+3)
  150 FORMAT(2X,16HVOLUME FRACTION ,A5,A1)
      READ(NREAD,*) V2(K)
      TEST=TEST+V2(K)
  160 CONTINUE
C---TEST TO SEE IF THE FRACTIONS SUM TO ONE
      TI=ABS(TEST-1.)
      IF(TI .LT. .001) GO TO 250
      WRITE(NWRITE,170)
  170 FORMAT(2X,19H* * INPUT ERROR * *//2X,13HTHE FRACTIONS
     C20H DO NOT SUM TO UNITY /2X,17HRE-ENTER THE DATA   )
      GO TO 140
C---ENTER COMPOSITION AS WEIGHT FRACTIONS
  180 TEST=0.
      DO 210 K=1,NUMB
```

```
      WRITE(NWRITE,190) PHASE(K),PHASE(K+3)
  190 FORMAT(2X,19HWEIGHT FRACTION OF  ,A5,A1)
      READ(NREAD,*) DX(K)
      WRITE(NWRITE,200) PHASE(K),PHASE(K+3)
  200 FORMAT(2X,10HDENSITY OF,1X,A5,A1)
      READ(NREAD,*) DEN(K)
      TEST=TEST+DX(K)
  210 CONTINUE
C---TEST TO SEE IF THE FRACTIONS SUM TO ONE
      TI=ABS(1.-TEST)
      IF(TI .LT. .001) GO TO 220
      WRITE(NWRITE,170)
      GO TO 180
  220 CONTINUE
C---CONVERT THE WEIGHT FRACTIONS TO VOLUME FRACTIONS
      SUM=0.
      DO 230 K=1,NUMB
      DELT(K)=DX(K)/DEN(K)
      SUM=SUM+DELT(K)
  230 CONTINUE
      DO 240 K=1,NUMB
      V2(K)=DELT(K)/SUM
  240 CONTINUE
  250 CONTINUE
C---ENTER FIBER'S ASPECT RATIO
      WRITE(NWRITE,260)
  260 FORMAT(2X,31HENTER ASPECT RATIO OF THE FIBER )
      READ(NREAD,*) AA2
C---ENTER PARAMETERS CONCERNING THE ORIENTATION PARAMETER "F"
      WRITE(NWRITE,270)
  270 FORMAT(2X,41HTHE STATE OF ORIENTATION OF THE FIBER IS
     C9HSPECIFIED/2X,34HBY THE HERMANS ORIENTATION FACTOR,1X
     C2HF./2X,23HFOR PLANAR RANDOM F = 0/2X,13HFOR PERFECTLY,1X
     C14HALIGNED F = 1.//2X,33HIF YOU WISH DATA FOR A SPECIFIED
     C30HORIENTATION ENTER A "0" (ZERO)/2X,15HIF YOU WISH TO
```

```
      C51HSCAN OVER A RANGE OF ORIENTATIONS ENTER A "1" (ONE) )
       READ(NREAD,30) MORN
       IF(MORN .EQ. 1) GO TO 290
       WRITE(NWRITE,280)
   280 FORMAT(2X,35HENTER SPECIFIC STATE OF ORIENTATION)
       READ(NREAD,*) FSTART
       FSTOP=FSTART
       FADD=.1
       GO TO 330
   290 WRITE(NWRITE,300)
   300 FORMAT(2X,32HENTER THE STARTING VALUE FOR "F")
       READ(NREAD,*) FSTART
       WRITE(NWRITE,310)
   310 FORMAT(2X,29HENTER THE FINAL VALUE FOR "F")
       READ(NREAD,*) FSTOP
       WRITE(NWRITE,320)
   320 FORMAT(2X,47HENTER THE INCREMENTS FOR STEPPING VALUES OF "F")
       READ(NREAD,*) FADD
   330 CONTINUE
       RETURN
       END
C* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
       SUBROUTINE ALTER(NUMB,ISO)
C
C          THIS SUBROUTINE PROVIDES FOR REPLACING THE STORED
C        VALUES OF YOUNG'S MODULUS, SHEAR MODULUS, AND POISSON'S
C        RATIO FOR ANYONE OR ALL OF THE COMPONENTS BY A SET OF
C        VALUES SELECTED BY THE USER.  IF THE NEW SET OF
C        VALUES IS TO BE USED TO REPRESENT A TRANSVERSELY
C        ISOTROPIC FIBER, THE USER WILL BE REQUIRED TO SUPPLY
C        TWO VALUES FOR THE YOUNG'S MODULUS (LONGITUDINAL AND
C        TRANSVERSE), TWO VALUES FOR THE SHEAR MODULUS, AND
C        TWO VALUES FOR THE POISSON'S RATIO.  ALTERED VALUES
C        WILL BE TESTED FOR SELF-CONSISTENCY.
C
```

```
C        INPUT:
                  NUMB     NUMBER OF COMPONENTS
                  MALT     FLAG TO INDICATE THAT THE STORED
C                          VALUES ARE TO ALTERED
C                 ISO      FLAG WHICH INDICATES WHETHER THE
C                          FIBER PHASE IS ISOTROPIC (ISO=0)
C                          OR ANISOTROPIC (ISO=1)
C
C        INPUT/OUTPUT:
C                 E1(I)    THE LONGITUDINAL YOUNG'S MODULUS FOR
C                          PHASE I
C                 E2(I)    THE TRANSVERSE YOUNG'S MODULUS FOR
C                          PHASE I
C                 E3(I)    THE PERPENDICULAR YOUNG'S MODULUS FOR
C                          PHASE I
C                 G12(I)   THE "1,2" SHEAR MODULUS FOR PHASE I
C                 G13(I)   THE "1,3" SHEAR MODULUS FOR PHASE I
C                 G23(I)   THE "2,3" SHEAR MODULUS FOR PHASE I
C               POS12(I)   THE "1,2" POISSON'S RATIO FOR PHASE I
C               POS13(I)   THE "1,3" POISSON'S RATIO FOR PHASE I
C               POS23(I)   THE "2,3" POISSON'S RATIO FOR PHASE I
C
C        FOR THE ABOVE ARRAYS:
C           I=1, RESIN PHASE
C           I=2, FIBER PHASE
C           I=3, FILLER PHASE
C
C        ROUTINES CALLED:
C           CHECK
C
      COMMON /B1/ NREAD,NWRITE
      COMMON /B3/ E1(3),E2(3),E3(3),G12(3),G13(3),G23(3),POS12(3),
     CPOS13(3),POS23(3),V2(3),AA2,FSTART,FSTOP,FADD
      DIMENSION PHASE(6)
      DATA PHASE/5HRESIN,5HFIBER,5HFILLE,2*1H ,1HR/
```

```
      DO 160 I=1,NUMB
C---DETERMINE IF THE I-TH PHASE PROPERTIES ARE TO BE CHANGED
      WRITE(NWRITE,10) PHASE(I),PHASE(I+3)
   10 FORMAT(2X,3HIF ,A5,A1,27H PROPERTIES ARE ACCEPTABLE
     C18HENTER A "0" (ZERO)/2X,25HIF THEY ARE TO BE ALTERED
     C18H ENTER A "1" (ONE))
      READ(NREAD,20) MALT
   20 FORMAT(I1)
      IF(MALT .EQ. 0) GO TO 160
      IF(I .EQ. 1 .OR. I .EQ. 3) GO TO 100
C---ENTER SYMMETRY OF FIBER
      WRITE(NWRITE,30)
   30 FORMAT(2X,40HIF FIBER IS ISOTROPIC ENTER A "0" (ZERO)/
     C2X,51HIF FIBER IS ANISOTROPIC (E.G. GRAPHITE) ENTER A "1"
     C,6H (ONE))
      READ(NREAD,35) ISO
   35 FORMAT(I1)
      IF(ISO .EQ. 0) GO TO 100
C---DETERMINE PROPERTIES FOR AN ANISOTROPIC FIBER
      WRITE(NWRITE,40)
   40 FORMAT(2X,34HENTER LONGITUDINAL YOUNG'S MODULUS)
      READ(NREAD,*) E1(2)
      WRITE(NWRITE,50)
   50 FORMAT(2X,32HENTER TRANSVERSE YOUNG'S MODULUS)
      READ(NREAD,*) E2(2)
      E3(2)=E2(2)
      WRITE(NWRITE,60)
   60 FORMAT(2X,24HENTER SHEAR MODULUS, G12)
      READ(NREAD,*) G12(2)
      G13(2)=G12(2)
      WRITE(NWRITE,70)
   70 FORMAT(2X,24HENTER SHEAR MODULUS, G23)
      READ(NREAD,*) G23(2)
      WRITE(NWRITE,80)
   80 FORMAT(2X,28HENTER POISSON'S RATIO, POS12  )
```

```
      READ(NREAD,*) POS12(2)
      POS13(2)=POS12(2)
      WRITE(NWRITE,90)
   90 FORMAT(2X,28HENTER POISSON'S RATIO, POS23   )
      READ(NREAD,*) POS23(2)
      GO TO 160
C---ENTER THE PROPERTIES FOR AN ISOTROPIC PHASE
  100 WRITE(NWRITE,110)PHASE(I),PHASE(I+3)
  110 FORMAT(2X,26HENTER YOUNG'S MODULUS FOR ,A5,A1)
      READ(NREAD,*) E1(I)
      E2(I)=E1(I)
      E3(I)=E1(I)
      WRITE(NWRITE,120) PHASE(I),PHASE(I+3)
  120 FORMAT(2X,24HENTER SHEAR MODULUS FOR ,A5,A1)
      READ(NREAD,*) G12(I)
      G13(I)=G12(I)
      G23(I)=G12(I)
      WRITE(NWRITE,130) PHASE(I),PHASE(I+3)
  130 FORMAT(2X,26HENTER POISSON'S RATIO FOR ,A5,A1)
      READ(NREAD,*) POS
C---CHECK FOR SELF-CONSISTENCY OF NEW INPUT DATA
  140 CALL CHECK(POS,G12(I),E1(I),P,MK)
      IF(MK .EQ. 1) GO TO 100
  150 POS12(I)=P
      POS13(I)=P
      POS23(I)=P
  160 CONTINUE
      RETURN
      END
```

```
C * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
      SUBROUTINE CHECK(POS,G,E,P,MK)
C---THIS SUBROUTINE CHECKS THE INPUT POISSON'S RATIO, POS,
C-- AGAINST POS=.5*(E/G)-1. TO ASSURE THAT THE INPUT IS
C-- CONSISTANT WITH AN ISOTROPIC MATERIAL
C
C       INPUT:
C               POS     INPUT POISSON'S RATIO
C               G       INPUT SHEAR MODULUS
C               E       INPUT YOUNG'S MODULUS
C
C       OUTPUT:
C               P       VALUE OF POISSON'S RATIO CONSISTANT
C                       WITH THE INPUT YOUNG'S MODULUS AND
C                       INPUT SHEAR MODULUS
C               MK      FLAG INDICATING SUCCESS OF NEW INPUT
C                       OPERATION
C
      COMMON /B1/ NREAD,NWRITE
      P=0.5*(E/G)-1.0
      IF(P.GT. 0. .AND. P .LT. .5) GO TO 20
C---THERE HAS BEEN AN INPUT ERROR, VALUES ARE UNACCEPTABLE
      WRITE(NWRITE,10)
   10 FORMAT(2X,19H* * INPUT ERROR * *//2X,9HFOR INPUT,1X
     C47HVALUES OF THE YOUNG'S MODULUS AND SHEAR MODULUS/2X,
     C44HPOISSON'S RATIO WOULD BE NEGATIVE OR GREATER,1X
     C8HTHAN 0.5//2X,13HRE-ENTER DATA)
      MK=1
      P=.3
      RETURN
   20 W=ABS(POS-P)
      IF(W .GT. .003) GO TO 30
C---THE ENTERED VALUE FOR POISSON'S RATIO IS ACCEPTABLE AND
C-- NEEDS NOT BE CHANGED
      MK=0
```

```
      P=POS
      RETURN
C---THE ENTERED POISSON'S RATIO IS INCONSISTENT WITH THE
C-- ENTERED YOUNG'S AND SHEAR MODULI, ASK IF VALUES ARE TO
C-- BE RE-ENTERED OR IF THE ESTIMATED VALUE IS ACCEPTABLE
   30 WRITE(NWRITE,40) P
   40 FORMAT(2X,19H* * INPUT ERROR * *//2X,10HTHE VALUES,1X
     C34HFOR THE MODULI AND POISSON'S RATIO/2X,3HARE,1X
     C38HINCONSISTENT FOR AN ISOTROPIC MATERIAL/2X,3HTHE,1X
     C41HPOISSON'S RATIO HAS BEEN ASSIGNED A VALUE,1X,F5.3)
      WRITE(NWRITE,50)
   50 FORMAT(2X,39HIF THIS ASSIGNMENT IS ACCEPTABLE, ENTER ,1X
     C13HA "0" (ZERO);/2X,27HOTHERWISE ENTER A "1" (ONE)/
     C2X,42HAND PREPARE TO RE-ENTER THE VALUES FOR THE/2X
     C51HYOUNG'S MODULUS, SHEAR MODULUS, AND POISSON'S RATIO)
      READ(NREAD,60) MK
   60 FORMAT(I1)
      RETURN
      END
C* * * * * * * * * * * * * * * * * * * * * * * * * * * *
      SUBROUTINE PRINT1(NUMB)
C---THIS SUBROUTINE IS USED TO PRINT THE INPUT DATA WHEN
C-- ALL PHASES ARE ISOTROPIC
      COMMON /B1/ NREAD,NWRITE
      COMMON /B3/ E1(3),E2(3),E3(3),G12(3),G13(3),G23(3),POS12(3),
     CPOS13(3),POS23(3),V2(3),AA2,FSTART,FSTOP,FADD
      DIMENSION PHASE(6)
      DATA PHASE/5HRESIN,5HFIBER,5HFILLE,2*1H ,1HR/
      WRITE(NWRITE,10) (PHASE(I),PHASE(I+3),E1(I),G12(I),POS12(I),
     CI=1,NUMB)
   10 FORMAT(11X,15HYOUNG'S MODULUS,3X,13HSHEAR MODULUS,3X,
     C15HPOISSON'S RATIO/2X,29(2H--)/(2X,A5,A1,5X,E10.4,
     C7X,E10.4,9X,F5.3))
      RETURN
      END
```

```
C* * * * * * * * * * * * * * * * * * * * * * * * * * * * *
      SUBROUTINE PRINT2(NUMB)
C---THIS ROUTINE IS USED TO PRINT THE INPUT DATA WHEN
C-- THE FIBER PHASE IS ANISOTROPIC
      COMMON /B1/ NREAD,NWRITE
      COMMON /B3/ DATA(3,10),AA2,FSTART,FSTOP,FADD
C---SET HEADINGS FOR OUTPUT
      DIMENSION TITLE(9),DASH(6),PHASE(6)
      DATA PHASE/5HRESIN,5HFIBER,5HFILLE,2*1H ,1HR/
      DATA DASH/2*5H-----,3H---,2*5H-----,3H---/
      DATA TITLE/2HE1,2HE2,2HE3,3HG12,3HG13,3HG23,5HPOS12,
     C5HPOS13,5HPOS23/
      WRITE(NWRITE,10) (PHASE(I),PHASE(I+3),I=1,NUMB)
   10 FORMAT(13X,A5,A1,7X,A5,A1,6X,A5,A1)
      NDASH=3
      IF(NUMB .EQ. 3) NDASH=6
      WRITE(NWRITE,20) (DASH(L),L=1,NDASH)
   20 FORMAT(2X,9(2H--),2(2A5,A3))
C---TYPE YOUNG'S AND SHEAR MODULI
      DO 40 L=1,6
      WRITE(NWRITE,30) TITLE(L),(DATA(J,L),J=1,NUMB)
   30 FORMAT(2X,A5,3X,3(E10.4,3X))
   40 CONTINUE
C---TYPE POISSON'S RATIOS
      DO 60 L=7,9
      WRITE(NWRITE,50) TITLE(L),(DATA(J,L),J=1,NUMB)
   50 FORMAT(2X,A5,6X,3(F5.3,8X))
   60 CONTINUE
      RETURN
      END
```

```
C* * * * * * * * * ** * * * * * * * * * * * * * * * * * * *
      SUBROUTINE ELAST(I,C)
C---CONVERTS THE ENGINEERING CONSTANTS (E=YOUNG'S MODULUS,
C-- G=SHEAR MODULUS, POS=POISSON'S RATIO) FOR PHASE "I" TO THE
C-- ARRAY OF ELASTIC CONSTANTS "C(J,K)"
      COMMON /B3/ E1(3),E2(3),E3(3),G12(3),G13(3),G23(3),POS12(3),
     CPOS13(3),POS23(3),V2(3),AA2,FSTART,FSTOP,FADD
      DIMENSION C(6,6)
C---CLEAR THE REGISTARS
      DO 10 K=1,6
      DO 10 J=1,6
      C(K,J)=0.
   10 CONTINUE
      AD=1.-2.*E3(I)/E1(I)*POS12(I)*POS23(I)*POS13(I)
     C-POS13(I)**2*E3(I)/E1(I)-POS23(I)**2*E3(I)/E2(I)-
     CPOS12(I)**2*E2(I)/E1(I)
      D=1./AD
      C(1,1)=E1(I)*D*(1.-((E3(I)/E2(I))*POS23(I)**2))
      C(1,2)=D*(E2(I)*POS12(I)+E3(I)*POS13(I)*POS23(I))
      C(2,2)=D*E2(I)*(1.-((POS13(I)**2)*(E3(I)/E1(I))))
      C(1,3)=D*E3(I)*(POS12(I)*POS23(I)+POS13(I))
      C(2,3)=D*(E3(I)/E1(I))*(E1(I)*POS23(I)+E2(I)*POS
     C12(I)*POS13(I))
      C(3,3)=D*E3(I)*(1.-(E2(I)/E1(I))*(POS12(I)**2))
      C(4,4)=G23(I)
      C(5,5)=G13(I)
      C(6,6)=G12(I)
      C(3,2)=C(2,3)
      C(3,1)=C(1,3)
      C(2,1)=C(1,2)
      RETURN
      END
```

```
C* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
      SUBROUTINE AMATIN(A,B,NWARN)
C---THIS SUBROUTINE INVERTS A 6X6 MATRIX WHICH HAS THE
C-- FOLLOWING PROPERTIES
C
C          A(I,J)=A(J,I)
C          A(I,J)=0.      FOR I NOT EQUAL J AND
C                         I OR J GREATER THAN 3
      DIMENSION NWARN(4),A(6,6),B(6,6)
      DO 10 K=1,4
       NWARN(K)=0.
   10 CONTINUE
C---CLEAR THE REGISTARS
      DO 20 K=1,6
      DO 20 J=1,6
       B(K,J)=0.
   20 CONTINUE
C---CALCULATE THE DETERMINANT OF THE MATRIX TO BE INVERTED
      DETER=A(1,1)*(A(2,2)*A(3,3)-A(3,2)*A(2,3))-A(1,2)*(A(2,1)
     C*A(3,3)-A(1,3)*A(3,2))+A(1,3)*(A(2,1)*A(3,2)-A(3,1)*
     CA(2,2))
C---CALCULATE THE ELEMENTS OF THE INVERTED MATRIX
   30 B(1,1)=(A(2,2)*A(3,3)-A(3,2)*A(2,3))/DETER
      B(2,2)=(A(1,1)*A(3,3)-A(3,1)*A(1,3))/DETER
      B(3,3)=(A(1,1)*A(2,2)-A(2,1)*A(1,2))/DETER
      B(1,2)=-(A(2,1)*A(3,3)-A(3,1)*A(2,3))/DETER
      B(1,3)=(A(2,1)*A(3,2)-A(2,2)*A(3,1))/DETER
      B(2,3)=-(A(1,1)*A(3,2)-A(3,1)*A(1,2))/DETER
      B(2,1)=B(1,2)
      B(3,1)=B(1,3)
      B(3,2)=B(2,3)
      DO 50 K=4,6
      IF(A(K,K) .NE. 0.) GO TO 40
      KK=K-2
      NWARN(KK)=1
```

```
      B(K,K)=9.99E10
      GO TO 50
   40 B(K,K)=1./A(K,K)
   50 CONTINUE
      RETURN
      END
C* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
      SUBROUTINE COMP(CZERO,PHASE,EZERO,PHASEM)
C---SUBROUTINE TO COMPUTE PHASE PROPERTIES COMPENSATED FOR
C-- CORRELATIONS
C
C      INPUT:
C              CZERO   THE 6X6 ARRAY OF ELASTIC CONSTANTS FOR
C                      THE REFERENCE PHASE
C              PHASE   THE 6X6 ARRAY OF ELASTIC CONSTANTS FOR
C                      THE CURRENT PHASE
C              EZERO   THE 6X6 ARRAY OF THE CORRELATION TENSOR
C
C      OUTPUT:
C              PHASEM  THE 6X6 ARRAY OF ELASTIC CONSTANTS FOR
C                      THE CURRENT PHASE COMPENSATED FOR
C                      CORRELATIONS
C
C      ROUTINES CALLED:
C              AMATIN
C
      DIMENSION CZERO(6,6),PHASE(6,6),EZERO(6,6),PHASEM(6,6)
      DIMENSION NDUM(4),NWARN(4),AAA(6,6),R(6,6),H(6,6)
C---CLEAR THE REGISTARS
      DO 5 J=1,6
      DO 5 K=1,6
       PHASEM(K,J)=0.
       R(K,J)=0.
       H(K,J)=0.
       AAA(K,J)=0.
```

```
      5 CONTINUE
        DO 10 K=1,6
        DO 10 J=1,6
        R(K,J)=PHASE(K,J)-CZERO(K,J)
     10 CONTINUE
        CALL AMATIN(R,AAA,NWARN)
C---DEVELOP THE INVERTED CORRELATION TENSOR
        DO 20 K=1,6
        DO 20 J=1,6
        H(K,J)=AAA(K,J)-EZERO(K,J)
     20 CONTINUE
        CALL AMATIN(H,PHASEM,NDUM)
C---CHECK TO SEE IF THE SHEAR MODULUS IN "R" WAS ZERO
        DO 30 K=4,6
        KK=K-2
        IF(NWARN(KK) .NE. 0) PHASEM(K,K)=0.
     30 CONTINUE
        RETURN
        END
C* * * * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
        SUBROUTINE EMAKE(EZERO,CZERO,AA)
C---THIS SUBROUTINE CREATES THE MATRIX EZERO
C
C          INPUT:
C                  AA       THE CURRENT ASPECT RATIO
C                  CZERO    THE 6X6 ARRAY OF ELASTIC CONSTANTS FOR
C                           THE REFERENCE PHASE
C
C          OUTPUT:
C                  EZERO    THE 6X6 ARRAY OF THE CORRELATION TENSOR
C
        DIMENSION EZERO(6,6),CZERO(6,6)
C---CLEAR THE REGISTARS
        DO 5 K=1,6
        DO 5 J=1,6
```

```
      EZERO(K,J)=0.
    5 CONTINUE
      IF(AA-1.) 10,50,60
C---SET THE H-I VALUES WHEN A IS LESS THAN ONE
C-
   10 IF(AA-.99) 30,30,20
C---DETERMINE THE H-I VALUES WHEN .99 < A < 1. USING
C-- APPROXIMATING POLYNOMIALS
   20 YSQ=(1.-AA*AA)/AA/AA
      Y4=YSQ*YSQ
      H1=2./3.-2.*YSQ/15.+2.*Y4/35.
      H2=1.-H1
      H3=8./15.-4.*YSQ/35.+Y4/10.
      H5=.2+4.*YSQ/35.+9.*Y4/10.
      H4=.5*(1.-H3-H5)
      GO TO 70
   30 IF(AA .GT. .025) GO TO 40
C---DETERMINE THE H-I VALUES WHEN 0. < A < .025 USING
C-- APPROXIMATING POLYNOMIALS
      PIE=ACOS(-1.)
      YSQI=AA*AA/(1.-AA*AA)
      YI=SQRT(YSQI)
      Y3I=YI**3
      Y4I=YSQI*YSQI
      H1=PIE*YI/2.-YSQI+(PIE-2.)*Y3I/2.+Y4I/3.
      H2=1.-H1
      H3=PIE*YI/4.-3.*Y3I*PIE/2.+4.*Y4I
      H5=1.-.75*PIE*YI+4.*YSQI-1.5*PIE*Y3I+4.*Y4I
      H4=.5*(1.-H3-H5)
      GO TO 70
C---WHEN .025 < A < .99 USING THE EXACT EQUATIONS AS DEVELOPED
C-- BY WU
   40 ASQ=AA**2
      B1=ASQ/(1.-ASQ)
      B1SQRT=SQRT(B1)
```

```
      B2=1./B1
      B2SQRT=SQRT(B2)
      B3=ATAN(B2SQRT)
      H1=B1*((B2SQRT+B1SQRT)*B3-1.)
      H2=1.-H1
      H3=B1**2*(.5/ASQ+1.+(B2**(1.5)/2.-B2SQRT-3.*B1SQRT/
     C2.)*B3)
      H5=(1.+ASQ/2.-3.*B1SQRT/2.*B3)/(1.-ASQ)**2
      H4=.5*(1.-H3-H5)
      GO TO 70
C---CALCULATE THE H-I VALUES FOR AN ASPECT RATIO OF ONE
   50 H1=2./3.
      H2=1./3.
      H3=8./15.
      H4=2./15.
      H5=1./5.
      GO TO 70
C---SET THE H-I VALUES WHEN A IS GREATER THAN ONE USING
C-- THE EXACT EQUATIONS DEVELOPED BY WU FOR 1.0 < A < 25.
   60 IF(AA .GT. 25.) GO TO 65
      X=(AA**2-1.)/AA**2
      XRT=SQRT(X)
      Z=ALOG((1.+XRT)/(1.-XRT))/XRT
      H1=(1.-.5*(1.-X)*Z)/X
      H2=1.-H1
      H3=(1.5-.5*X+.25*(X**2+2.*X-3.)*Z)/X**2
      H5=(((1.-X)/X)**2)*(((3.-2.*X)/(2.*(1.-X)))-.75*Z)
      H4=.5*(1.-H3-H5)
      GO TO 70
C---WHEN 25 < A < 150 USE THE APPROXIMATING POLYNOMILAL
   65 IF(AA .GT. 150.) GO TO 85
      XSQ=(AA*AA-1.)/AA/AA
      HG=.2+XSQ*(1./7.+XSQ/9.)
      B1=(1.-XSQ)*XSQ*HG
      H1=(2.+XSQ)/3.-B1
      H2=1.-H1
```

```
      H3=(16.+XSQ*(11.+3.*XSQ))/30.-(3.+2.*XSQ)*B1/2.
      H5=(1.-XSQ)*(2.+3.*XSQ)/10.-3.*B1/2.
      H4=.5*(1.-H3-H5)
C---CALCULATE THE CONSTANTS WHICH CAN BE COMBINED TO GIVE
C-- THE MATRIX EZERO
   70 ALPHA=(CZERO(2,2)-CZERO(4,4))/(4.*CZERO(4,4)*CZERO(2,2))
      BETA=.25/CZERO(6,6)
      AKE=ALPHA*H3-BETA*H1
      AMUE=.5*ALPHA*H3-BETA*H1
      ALAMBE=2.*ALPHA*H4
      DELTA=2.*ALPHA*H4-BETA*(.5*H1+H2)
      RNE=4.*ALPHA*H5-4.*BETA*H2
C---CALCULATE THE COMPONENTS OF THE EZERO MATRIX
      EZERO(1,1)=RNE
      EZERO(1,2)=ALAMBE
      EZERO(1,3)=EZERO(1,2)
      EZERO(2,1)=EZERO(1,2)
      EZERO(2,2)=AKE+AMUE
      EZERO(2,3)=AKE-AMUE
      EZERO(3,1)=EZERO(1,3)
      EZERO(3,2)=EZERO(2,3)
      EZERO(3,3)=EZERO(2,2)
      EZERO(4,4)=4.*AMUE
      EZERO(5,5)=4.*DELTA
      EZERO(6,6)=EZERO(5,5)
      GO TO 90
C---COMPUTE EZERO FOR A APPROACHING INFINITY FOR THE GENERAL
C-- CASE OF TRANSVERSELY ISOTROPIC REFERENCE
   85 EKT=-.25/CZERO(2,2)
      EMUT=-(CZERO(2,2)+CZERO(4,4))/(8.*CZERO(4,4)*CZERO(2,2))
      EMUA=-.125/CZERO(5,5)
      EZERO(2,2)=EKT+EMUT
      EZERO(2,3)=EKT-EMUT
      EZERO(3,3)=EZERO(2,2)
      EZERO(3,2)=EZERO(2,3)
```

```
      EZERO(4,4)=4.*EMUT
      EZERO(5,5)=4.*EMUA
      EZERO(6,6)=EZERO(5,5)
   90 CONTINUE
      RETURN
      END
C* * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
      SUBROUTINE PLANAR(B,F,A,AA)
C---CONSTRUCTS THE PLANAR AVERAGE "AA" OF ARRAY "A" FOR EITHER
C-- ELASTIC CONSTANTS (B=1.0) OR COMPLIANCE CONSTANTS (B=4.)
C-- FOR THE STATE OF ORIENTATION "F"
      DIMENSION A(6,6),AA(6,6),AD(6,6),AZ(6,6)
C---CLEAR THE REGISTERS
      DO 10 K=1,6
      DO 10 J=1,6
      AA(K,J)=0.
      AD(K,J)=0.
      AZ(K,J)=0.
   10 CONTINUE
C---COMPUTE ASSOCIATED VALUE OF ORIENTATION PARAMETER "G"
      G=2.*F*(7.-2.*F)/(5.*(4.-2.*F))
C---SET UP INVARIANTS
      AZ(1,1)=(3.*A(1,1)+3.*A(2,2)+2.*A(1,2)+4./B*A(6,6))/8.
      AZ(2,2)=AZ(1,1)
      AZ(1,2)=(A(1,1)+A(2,2)+6.*A(1,2)-4./B*A(6,6))/8.
      AZ(1,3)=(A(1,3)+A(2,3))/2.
      AZ(2,3)=AZ(1,3)
      AZ(3,1)=AZ(1,3)
      AZ(3,2)=AZ(2,3)
      AZ(3,3)=A(3,3)
      AZ(4,4)=(A(4,4)+A(5,5))/2.
      AZ(5,5)=AZ(4,4)
      AZ(6,6)=B*(A(1,1)+A(2,2)-2.*A(1,2)+4./B*A(6,6))/8.
      DO 20 K=1,6
      DO 20 J=1,6
```

```
      AD(K,J)=AZ(K,J)-A(K,J)
   20 CONTINUE
C---CONSTRUCT AVERAGES
      DO 30 K=1,6
      DO 30 J=1,6
      AA(K,J)=AZ(K,J)-F*AD(K,J)
   30 CONTINUE
C---COMPLETE CONSTRUCTION WITH "G" DEPENDENT TERMS
      AA(1,1)=AA(1,1)+(5.*(G-F)*AD(6,6))/B
      AA(1,2)=AA(1,2)-5.*(G-F)*AD(1,2)
      AA(2,1)=AA(1,2)
      AA(2,2)=AA(2,2)+(5.*(G-F)*AD(6,6))/B
      AA(6,6)=AA(6,6)-5.*(G-F)*AD(6,6)
      RETURN
      END
C* * * * * * * * * * * * * * * * * * * * * * * * * * * * * *
      SUBROUTINE SMIX(VHI,CLO,CHI,CM)
C
C         THIS ROUTINE USES THE WU-MCCULLOUGH RELATIONSHIP IN
C       CONJUNCTION WITH THE S-MIXING RULE TO GENERATE PROPERTIES
C       FOR PARTICULATE SYSTEMS (ASPECT RATIO = 1).
C
C       INPUT:
C               VHI     VOLUME FRACTION OF RIGID PHASE
C               CLO     6X6 ARRAY OF ELAXTIC CONSTANTS FOR SOFT
C                       PHASE
C               CHI     6X6 ARRAY OF ELASTIC CONSTANTS FOR
C                       RIGID PHASE
C
C       OUTPUT:
C               CM      6X6 ARRAY OF ELASTIC CONSTANTS FOR A
C                       PARTICULATE SYSTEM
C
C       ROUTINES CALLED:
C               EMAKE
```

```
C                    COMP
C                    AMATIN
C
      DIMENSION CLO(6,6),CHI(6,6),CM(6,6),BIGM(6,6),TRANS(6,6)
      DIMENSION AAA(6,6),SL(6,6),SH(6,6),EZERO(6,6),CSTAR(6,6)
      DIMENSION NDUM(4)
C---CLEAR THE REGISTARS
      DO 10 K=1,6
      DO 10 J=1,6
       CM(K,J)=0.
       BIGM(K,J)=0.
       TRANS(K,J)=0.
       AAA(K,J)=0.
       SL(K,J)=0.
       SH(K,J)=0.
   10 CONTINUE
      IF(VHI .EQ. 0.) GO TO 40
C---COMPUTE LOWER BOUND FOR A PARTICULATE SYSTEM (AA=1)
      CALL EMAKE(EZERO,CLO,1.)
      CALL COMP(CLO,CHI,EZERO,TRANS)
      DO 20 K=1,6
      DO 20 J=1,6
       BIGM(K,J)=VHI*TRANS(K,J)
   20 CONTINUE
      CALL AMATIN(BIGM,TRANS,NDUM)
      DO 30 K=1,6
      DO 30 J=1,6
       AAA(K,J)=TRANS(K,J)+EZERO(K,J)
   30 CONTINUE
      CALL AMATIN(AAA,TRANS,NDUM)
   40 DO 50 K=1,6
      DO 50 J=1,6
       CSTAR(K,J)=CLO(K,J)+TRANS(K,J)
   50 CONTINUE
      CALL AMATIN(CSTAR,SL,NDUM)
C---COMPUTE UPPER BOUND FOR A PARTICULATE SYSTEM (AA=1)
```

```
      CALL EMAKE(EZERO,CHI,1.)
      CALL COMP(CHI,CLO,EZERO,TRANS)
      DO 60 K=1,6
      DO 60 J=1,6
       BIGM(K,J)=(1.-VHI)*TRANS(K,J)
   60 CONTINUE
      CALL AMATIN(BIGM,TRANS,NDUM)
      DO 70 K=1,6
      DO 70 J=1,6
       AAA(K,J)=TRANS(K,J)+EZERO(K,J)
   70 CONTINUE
      CALL AMATIN(AAA,TRANS,NDUM)
      DO 80 K=1,6
      DO 80 J=1,6
       CSTAR(K,J)=CHI(K,J)+TRANS(K,J)
   80 CONTINUE
      CALL AMATIN(CSTAR,SH,NDUM)
C---COMPUTE ELASTIC CONSTANTS BY MIXING RULE
      VOL=1.-VHI
      DO 90 K=1,6
      DO 90 J=1,6
       TRANS(K,J)=VOL*SL(K,J)+VHI*SH(K,J)+.5*VHI*VOL*
     C (SL(K,J)-SH(K,J))
   90 CONTINUE
C---CONVERT COMPLIANCE TO ELASTIC CONSTANTS
      CALL AMATIN(TRANS,CM,NDUM)
      RETURN
      END
```

Anticipated Modifications

The program SMC-3 was constructed from basic FORTRAN statements in order to facilitate its transferability. The program could be made more efficient by using statements unique to specific computers.

Currently SMC-3 is executed on a DEC-10 system. For this system, no "job" control cards are required. Consequently, there are no file or tape declaration statements, no calls to specific compilers, and no memory or time limit specifications. The following items are summarized for the benefit of users concerned with such requirements.

- Tapes Declared: SMC-3 uses only input and output tapes
- Compiler: SMC-3 is FORTRAN-10 compatible
- Memory Requirements: SMC-3 uses less than the default memory limit on the DEC-10
- Time Limit: CPU time is usually less than one second

It was recognized that the READ and WRITE device number would vary with the user's computer system. In order to facilitate transfer, SMC-3 has incorporated integer variables for input and output device numbers. Both variables, NREAD for input device, NWRITE for output device, are assigned values using a DATA statement (line 12100 of the program). The typical input/output commands in SMC-3 are of the form

```
DATA NREAD,NWRITE/5,5/
   .
   .
   .
READ(NREAD,10)A
   .
   .
   .
WRITE(NWRITE,100)A
```

To assign the correct device numbers to the READ and WRITE statements, it is only necessary to change the DATA statement (line 12100). The variables NREAD and NWRITE are transferred to the required subroutines through COMMON/B1/. For ease of data entry, SMC-3 was written using free formatted READ statements. The free format READ symbol for the DEC-10 is the star, "*". These READ statements are of the form:

```
READ(NREAD,*)B
```

If the computing system on which SMC-3 is being implemented has free format READ capabilities, the correct symbol will need to be used in place of the star. For systems which do not have the free format READ options, it will be necessary to format each of the existing free format READ commands. Young's and Shear moduli could be read using the exponential field format--an E10.5 field would suffice. All other formats could be replaced by a floating point field. For example, a F20.10 would suffice. If this is done, all data should be entered including decimal points. <u>Statement numbers for the added FORMAT statements should be 500 or longer</u> to prevent any duplication of existing statement numbers.

To replace the free formatted READ statements, the following changes will be necessary:

1) change free format symbol, "*", to FORMAT statement numbers

2) insert corresponding FORMAT statement

For example, the READ statement which reads the volume fractions (program line 30300) could be changed to:

```
    READ(NREAD,500)V2(K)
500 FORMAT(F20.10)
```

The READ command for Young's modulus (program line 46500) could be rewritten as:

```
    READ(NREAD,510) E1(I)
510 FORMAT (E10.5)
```

A listing of each line where the free format has been utilized is summarized below. Lines 30300 through 36800 are all contained in SUBROUTINE INPUT. All these lines can be replaced with a single floating point FORMAT statement. The remaining free formatted READ statements occur in SUBROUTINE ALTER. Both exponential field and floating point field FORMAT statements will need to be used in this subroutine. POS12(2), POS23(2) and POS should be read using the floating point field while the remaining variables can be read using the suggested exponential field.

(From SUBROUTINE INPUT)

```
30300          READ(NREAD,*) V2(K)
31800          READ(NREAD,*) DX(K)
32100          READ(NREAD,*) DEN(K)
34300          READ(NREAD,*) AA2
35600          READ(NREAD,*) FSTART
36200          READ(NREAD,*) FSTART
36500          READ(NREAD,*) FSTOP
36800          READ(NREAD,*) FADD
```

(From SUBROUTINE ALTER)

```
44200          READ(NREAD,*) E1(2)
44500          READ(NREAD,*) E2(2)
44900          READ(NREAD,*) G12(2)
45300          READ(NREAD,*) G23(2)
45600          READ(NREAD,*) POS12(2)
46000          READ(NREAD,*) POS23(2)
46500          READ(NREAD,*) E1(I)
47000          READ(NREAD,*) G12(I)
47500          READ(NREAD,*) POS
*
```

Another change which may be necessary deals with continuation cards. In two FORMAT statements, the number of continuation cards has exceeded four. Seven were used starting at line 20000 while six were used starting at line 34600. For computers/compilers which are limited to fewer continuation cards, the output at these two locations will need to be rewritten using two WRITE statements.

SPECIALIZED TI-59 ROUTINES

Introduction

This section describes the operation of a TI-59 calculator/ PC-100 printer programmed to predict properties for two-component (fiber/resin) and three component (fiber/filler/resin) sheet molding materials.

The program is segmented on four magnetic cards:

Card I -- Reads input and generates reference phase

Card II -- Generates CSTAR

Card III -- Planar averaging

Card IV -- Generates Engineering constants and controls output.

The procedures for reading magnetic cards are reviewed at the end of this section.

A PC-100 printer is required for the operation of the program.

The current version of the program is restricted to isotropic fibers with aspect ratios in excess of 150. Supplementary cards will be provided at a future date to deal with low aspect ratio fibers and platelet reinforcing agents.

The following input data is required:

E_j = Young's modulus of component "j"

ν_j = Poisson's ratio of component "j"

G_j = Shear modulus of component "j"

v_j = volume fraction of component "j"

f = orientation parameter, $0 \leq f \leq 1$
(f=0 is random, f=1 is perfectly aligned)

The operating procedures for two-phase and three-phase systems are summarized in the following section. Sample calculations are given in the subsequent section.

Preprogrammed magnetic cards will be provided. However, difficulty has been encountered in reading magnetic cards programmed on other machines. Consequently, a program listing is provided so that cards can be generated.

OPERATING PROCEDURES FOR TWO-PHASE SYSTEMS

☐ Enter physical properties

☐ Read sides 1 and 2 of card I

	Press	Display	Printer
☐ Enter resin properties			
☐ E_R	A	E_R	E_R
☐ ν_R	B	ν_R	ν_R
☐ G_R	C	G_R	G_R
☐ Enter fiber properties			
☐ E_F	2nd A'	E_F	E_F
☐ ν_F	2nd B'	ν_F	ν_F
☐ G_F	2nd C'	G_F	G_F
☐ Enter volume fraction fiber	D	v_F	v_F
☐ Generate reference phase properties	E	0	E_{Ref}
			ν_{Ref}
			G_{Ref}

☐ Card II

☐ Read sides 1 and 2 of card II

☐ Press A

Printer will respond with a print and advance when finished

☐ Planar averaging

☐ Read sides 1 and 2 of card III

	Press	Display	Printer	
☐ Enter orientation parameter f	A	f	f	F
Planar averaging	B	0	Will advance when completed	
☐ Output				
☐ Read sides 1 only of Card IV				
☐ Generate output	A	0		E1 E2 E3 V12 V13 V23 G23 G13 G12

SUMMARY OF RESULTS

▷ To vary f, the orientation parameter: Run the program as before, with the first value of f.

▷ After obtaining the necessary output, read side 1 (only) of card III

▷ Enter orientation parameter, f, and continue with planar averaging operation

OPERATING PROCEDURES FOR THREE-PHASE SYSTEMS

☐ Enter physical properties of resin and filler

☐ Read sides 1 and 2 of card I

	Press	Display	Printer
☐ Enter resin properties			
☐ E_R	A	E_R	E_R
☐ ν_R	B	ν_R	ν_R
☐ G_R	C	G_R	G_R
☐ Enter filler properties			
☐ E_{Fill}	2nd A'	E_{Fill}	E_{Fill}
☐ ν_{Fill}	2nd B'	ν_{Fill}	ν_{Fill}
☐ G_{Fill}	2nd C'	G_{Fill}	G_{Fill}
☐ Enter modified volume fraction filler	D	v'_{Fill}	v'_{Fill}

$$v'_{Fill} = \frac{v_{Fill}}{v_{Fill}+v_R}$$

	Press	Display	Printer
☐ Generate surrogate matrix properties	E		E_m
			ν_m
			G_m

☐ Enter physical properties of surrogate matrix and fiber

	Press	Display	Printer
☐ Enter surrogate matrix properties			
☐ E_m	A	E_m	E_m
☐ ν_m	B	ν_m	ν_m
☐ G_m	C	G_m	G_m

	Press	Display	Printer
□ Enter fiber properties			
□ E_F	2nd A'	E_F	E_F
□ ν_F	2nd B'	F	F
□ G_F	2nd C'	G_F	G_F
□ Enter volume fraction fiber	D	V_F	V_F
□ Generate reference phase properties	E		E_{Ref}
			ν_{Ref}
			G_{Ref}

☆ AT THIS POINT, CONTINUE WITH CARD II
AS IN THE TWO-PHASE PROGRAM

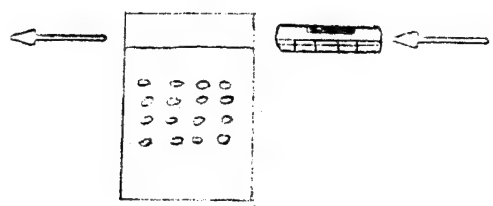
REVIEW OF CARD READING PROCEDURES

I. Reading Cards

All program cards need both sides read except the output program. When an instruction tells you to read both sides of a card:

A. Press CLR

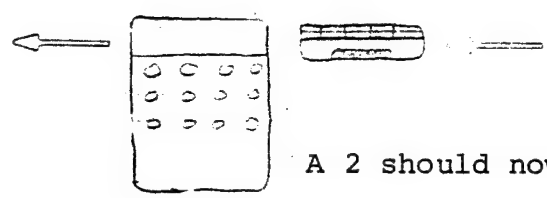
B. Slide card through lower slot in calculator, printed side up:



The card-reader motor will start. Push the card in until the gears catch it and pull it through. Pull the card out from the other side. A 1 should be in the display.

C. Press CLR

D. Turn card around and slide through again (printed side still up.



A 2 should now be in the display.

E. If display flashes, press CLR and try again.

F. If motor continues to run and display is blank after reading a card, press R/S. There wasn't anything on the side you read. Make sure the card was supposed to have both sides read.

EXAMPLES

EXAMPLES RUN WITH A TWO-PHASE COMPOSITE

SMC-65 Properties (in psi)

	E	ν	G	Vol. Fraction
Resin	5.1×10^{5}	.301	1.96×10^{5}	.6
Fiber	1.05×10^{7}	.333	3.94×10^{6}	.4

☐ Read sides 1 and 2 of card I

	Press	Display	Printer
Enter resin properties			
☐ 5.1 EE 5	A	5.1 05	5.1 05
☐ .301	B	3.01 -01	3.01-01
☐ 1.96 EE 5	C	1.96 05	1.96 05
Enter fiber properties			
☐ 1.05 EE7	2nd A'	1.05 07	1.05 07
☐ .333	2nd B'	3.33 -01	3.33-01
☐ 3.94 EE 6	2nd C'	3.94 06	3.94 06
Volume fraction fiber			
☐ .4	D	4. -01	4. -01
☐ Generate reference phase properties	E	0	1.340 06 2.821-01 5.225 05
☐ Read sides 1 and 2 of card II			
☐ Run program on this card	A	0.	0.
☐ Read sides 1 and 2 of card III			
Enter f			
☐ 0.	A	0	0. F
☐ Planar averaging	B	0	Printer advance when done

☐ Read side 1 of card IV

	Press	Display	Printer
☐ Generate output	A	0	2.377 06 E1 2.377 06 E2 1.319 06 E3 2.950-01 V12 3.010-01 V13 3.010-01 V23 5.082 05 G23 5.082 05 G13 9.176 05 G12
SUMMARY OF RESULTS			
☐ Read side 1 of card III			
Enter new f value			
☐ .25	A	.25	0.25 F
☐ Planar averaging	B	0	
☐ Read side 1 of card IV			
☐ Generate output	A	0	2.705 06 E1 1.949 06 E2 1.315 06 E3 3.680-01 V12 2.770-01 V13 3.070-01 V23 4.955 05 G23 5.209 05 G13 9.432 05 G12
SUMMARY OF RESULTS			

SAMPLE RUN WITH A THREE-PHASE COMPOSITE

SMC-25 Properties (in psi)

	E	ν	G	Vol. Fraction
Resin	5.1×10^5	.301	1.96×10^5	.504
Fiber	1.05×10^7	.333	3.94×10^6	.179
Filler	3×10^6	.402	1.07×10^6	.317

☐ Read sides 1 and 2 of card I

	Press	Display	Printer
Enter resin properties			
☐ 5.1 EE5	A	5.1 05	5.1 05
☐ .301	B	3.01 -01	3.01 -01
☐ 1.96 EE5	C	1.96 05	1.96 05
Enter filler properties			
☐ 3 EE6	2nd A'	3. 06	3. 06
☐ .042	2nd B'	4.02 -01	4.02 -01
☐ 1.07 EE 6	2nd C'	1.07 06	1.07 06

Enter modified volume fraction filler:

$$v_{Fill} = \frac{v_{Fill}}{v_{Fill} + v_R}$$

	Press	Display	Printer
☐ $v'_{Fill} = \frac{.317}{.317 + .504} = .3861$	D	3.861-01	3.861-01
☐ Generate surrogate matrix properties	E	0	9.582 05 3.117-01 3.652 05
Enter surrogate matrix properties			
☐ 9.582 EE5	A	9.582 05	9.582 05
☐ .3117	B	3.117-01	3.117-01
☐ 3.652 EE5	C	3.652 05	3.652 05
Enter fiber properties			
☐ 1.05 EE 7	2nd A'	1.05 07	1.05 07
☐ .333	2nd B'	3.33 -01	3.33 -01
☐ 3.94 EE 6	2nd C'	3.94 06	3.94 06

	Press	Display	Printer
Volume fraction fiber			
☐ .179	D	1.79 -01	1.79-01
☐ Generate reference phase properties	E	0	1.348 06 3.021-01 5.175 05
☐ Read sides 1 and 2 of card II			
☐ Run program on this card	A	0.	0.
☐ Read sides 1 and 2 of card III			
Enter f			
☐ 0	A	0	0. F
☐ Planar averaging	B	0	1 advance
☐ Read side 1 of card IV			
☐ Generate output	A		1.756 06 E1 1.756 06 E2 1.356 06 E3 3.080-01 V12 3.110-01 V13 3.110-01 V23 4.975 05 G23 4.975 05 G13 6.710 05 G12
SUMMARY OF RESULTS (f=0)			
☐ Read side 1 of card III			
Enter new f value			
☐ .25	A	.25	0.25 F
☐ Planar averaging	B	0	
☐ Read side 1 of card IV			
☐ Generate output	A	0	1.894 06 E1 1.576 06 E2 1.353 06 E3 3.480-01 V12 2.960-01 V13 3.170-01 V23 4.936 05 G23 5.014 05 G13 6.823 05 G12
SUMMARY OF RESULTS (f=0.25)			

TI-59

PROGRAM LISTINGS

The key strokes associated with cards I-IV are listed on the following pages.

It is recommended that upon entering the routines, duplicate magnetic cards should be recorded. The spare card serves as a replacement for a damaged card. If a card is damaged, a second duplicate should be recorded from the spare card.

C A R D I

Data Input and Generation of Reference Phase

Labels Used

001	22	INV
043	11	A
051	12	B
067	13	C
086	16	A'
094	17	B'
110	18	C'
129	14	D
137	15	E
176	52	EE
247	57	ENG
256	33	X²
277	34	√X
316	89	π
327	68	NOP
391	78	Σ+
414	70	RAD

Program

000	76	LBL
001	22	INV
002	73	RC*
003	10	10
004	33	X²
005	85	+
006	73	RC*
007	10	10
008	65	×
009	73	RC*
010	11	11
011	75	-
012	02	2
013	65	×
014	73	RC*
015	11	11
016	33	X²
017	95	=
018	42	STO
019	13	13
020	35	1/X
021	65	×
022	53	(
023	73	RC*
024	11	11
025	85	+
026	73	RC*
027	10	10
028	54	)
029	95	=
030	72	ST*
031	10	10
032	73	RC*
033	11	11
034	55	÷
035	43	RCL
036	13	13
037	94	+/-
038	95	=
039	72	ST*
040	11	11
041	92	RTN
042	76	LBL
043	11	A
044	35	1/X
045	42	STO
046	30	30
047	35	1/X
048	99	PRT
049	91	R/S
050	76	LBL
051	12	B
052	65	×
053	43	RCL
054	30	30
055	94	+/-
056	95	=
057	42	STO
058	31	31
059	55	÷
060	43	RCL
061	30	30
062	94	+/-
063	95	=
064	99	PRT
065	91	R/S
066	76	LBL
067	13	C
068	42	STO
069	32	32
070	03	3
071	00	0
072	42	STO
073	10	10
074	03	3
075	01	1
076	42	STO
077	11	11
078	71	SBR
079	22	INV
080	43	RCL
081	32	32
082	99	PRT
083	98	ADV
084	91	R/S
085	76	LBL
086	16	A'
087	35	1/X
088	42	STO
089	33	33
090	35	1/X
091	99	PRT
092	91	R/S
093	76	LBL
094	17	B'
095	65	×
096	43	RCL
097	33	33
098	94	+/-
099	95	=
100	42	STO
101	34	34
102	55	÷
103	43	RCL
104	33	33
105	94	+/-
106	95	=
107	99	PRT
108	91	R/S
109	76	LBL
110	18	C'
111	42	STO
112	35	35
113	03	3
114	03	3
115	42	STO
116	10	10
117	03	3
118	04	4
119	42	STO
120	11	11
121	71	SBR
122	22	INV
123	43	RCL
124	35	35
125	99	PRT

CARD I
-continued-

126	98	ADV	
127	91	R/S	
128	76	LBL	
129	14	D	
130	42	STO	
131	42	42	
132	42	STO	
133	50	50	
134	99	PRT	
135	91	R/S	
136	76	LBL	
137	15	E	
138	43	RCL	
139	33	33	
140	75	-	
141	43	RCL	
142	30	30	
143	95	=	
144	42	STO	
145	43	43	
146	43	RCL	
147	34	34	
148	75	-	
149	43	RCL	
150	31	31	
151	95	=	
152	42	STO	
153	44	44	
154	43	RCL	
155	35	35	
156	75	-	
157	43	RCL	
158	32	32	
159	95	=	
160	35	1/X	
161	42	STO	
162	45	45	
163	04	4	
164	03	3	
165	42	STO	
166	10	10	
167	04	4	
168	04	4	
169	42	STO	
170	11	11	
171	71	SBR	
172	22	INV	
173	61	GTO	
174	57	ENG	
175	76	LBL	
176	52	EE	
177	73	RC*	
178	00	00	
179	75	-	
180	73	RC*	
181	02	02	
182	95	=	
183	55	÷	
184	04	4	
185	55	÷	
186	73	RC*	
187	00	00	
188	55	÷	
189	73	RC*	
190	02	02	
191	95	=	
192	42	STO	
193	46	46	
194	04	4	
195	65	×	
196	73	RC*	
197	02	02	
198	95	=	
199	35	1/X	
200	42	STO	
201	47	47	
202	65	×	
203	04	4	
204	55	÷	
205	03	3	
206	94	+/-	
207	85	+	
208	04	4	
209	55	÷	
210	05	5	
211	65	×	
212	43	RCL	
213	46	46	
214	95	=	
215	72	ST*	
216	06	06	
217	04	4	
218	55	÷	
219	01	1	
220	05	5	
221	65	×	
222	43	RCL	
223	46	46	
224	95	=	
225	72	ST*	
226	07	07	
227	01	1	
228	06	6	
229	55	÷	
230	01	1	
231	05	5	
232	65	×	
233	43	RCL	
234	46	46	
235	75	-	
236	08	8	
237	55	÷	
238	03	3	
239	65	×	end side 1-
240	43	RCL	
241	47	47	
242	95	=	
243	72	ST*	
244	08	08	
245	92	RTN	
246	76	LBL	
247	57	ENG	
248	03	3	
249	08	8	
250	42	STO	
251	00	00	
252	08	8	
253	42	STO	
254	09	09	
255	76	LBL	
256	33	X^2	
257	43	RCL	
258	00	00	
259	72	ST*	
260	09	09	
261	01	1	
262	94	+/-	
263	44	SUM	
264	00	00	
265	97	DSZ	
266	09	09	
267	33	X^2	
268	71	SBR	
269	52	EE	
270	08	8	
271	42	STO	
272	09	09	

CARD I
-continued-

273	03	3	322	71	SBR	371	42	STO
274	44	SUM	323	68	NOP	372	10	10
275	00	00	324	61	GTO	373	43	RCL
276	76	LBL	325	78	Σ+	374	07	07
277	34	√X	326	76	LBL	375	42	STO
278	03	3	327	68	NOP	376	11	11
279	74	SM*	328	43	RCL	377	71	SBR
280	09	09	329	46	46	378	22	INV
281	97	DSZ	330	64	PD*	379	73	RC*
282	09	09	331	06	06	380	00	00
283	34	√X	332	64	PD*	381	74	SM*
284	71	SBR	333	07	07	382	06	06
285	52	EE	334	64	PD*	383	73	RC*
286	01	1	335	08	08	384	01	01
287	94	+/-	336	43	RCL	385	74	SM*
288	44	SUM	337	43	43	386	07	07
289	42	42	338	55	÷	387	71	SBR
290	43	RCL	339	43	RCL	388	22	INV
291	42	42	340	42	42	389	92	RTN
292	35	1/X	341	95	=	390	76	LBL
293	85	+	342	74	SM*	391	78	Σ+
294	01	1	343	06	06	392	01	1
295	95	=	344	43	RCL	393	75	-
296	42	STO	345	44	44	394	43	RCL
297	46	46	346	55	÷	395	42	42
298	71	SBR	347	43	RCL	396	95	=
299	68	NOP	348	42	42	397	42	STO
300	01	1	349	95	=	398	46	46
301	44	SUM	350	74	SM*	399	55	÷
302	42	42	351	07	07	400	02	2
303	43	RCL	352	43	RCL	401	65	×
304	46	46	353	45	45	402	43	RCL
305	35	1/X	354	55	÷	403	42	42
306	42	STO	355	43	RCL	404	95	=
307	46	46	356	42	42	405	42	STO
308	08	8	357	85	+	406	47	47
309	42	STO	358	73	RC*	407	03	3
310	09	09	359	08	08	408	42	STO
311	03	3	360	95	=	409	09	09
312	94	+/-	361	35	1/X	410	01	1
313	44	SUM	362	85	+	411	44	SUM
314	00	00	363	73	RC*	412	08	08
315	76	LBL	364	02	02	413	76	LBL
316	89	π	365	95	=	414	70	RAD
317	74	SM*	366	35	1/X	415	43	RCL
318	09	09	367	72	ST*	416	46	46
319	97	DSZ	368	08	08	417	65	×
320	09	09	369	43	RCL	418	73	RC*
321	89	π	370	06	06	419	06	06

CARD I
-continued-

```
420  85   +
421  43  RCL
422  42   42
423  65   ×
424  73  RC*
425  08   08
426  85   +
427  43  RCL
428  47   47
429  65   ×
430  53   (
431  73  RC*
432  06   06
433  75   -
434  73  RC*
435  08   08
436  54   )
437  95   =
438  72  ST*
439  06   06
440  01   1
441  44  SUM
442  06   06
443  44  SUM
444  08   08
445  97  DSZ
446  09   09
447  70  RAD
448  58  FIX
449  03   03
450  52  EE
451  95   =
452  98  ADV
453  43  RCL
454  36   36
455  35  1/X
456  99  PRT
457  65   ×
458  43  RCL
459  37   37
460  94  +/-
461  95   =
462  99  PRT
463  43  RCL
464  38   38
465  35  1/X
466  99  PRT
467  98  ADV
468  42  STO
469  38   38
470  71  SBR
471  22  INV
472  58  FIX
473  09   09
474  25  CLR
475  91  R/S
```

NOTE: Intermediate results for CZERO are stored in the following registers

Reg 36: $C_{11} = C_{22} = C_{33}$

37: $C_{12} = C_{13} = C_{23}$

38: $C_{44} = C_{55} = C_{66}$

C A R D   II

Calculation of CSTAR

Labels used

001	22	INV
043	11	A
126	85	+
148	49	PRD
249	24	CE
254	53	(
298	54	)
351	78	Σ+
370	35	1/X

Program

000	76	LBL
001	22	INV
002	43	RCL
003	10	10
004	33	X²
005	85	+
006	43	RCL
007	10	10
008	65	×
009	43	RCL
010	11	11
011	75	-
012	02	2
013	65	×
014	43	RCL
015	11	11
016	33	X²
017	95	=
018	42	STO
019	12	12
020	35	1/X
021	65	×
022	53	(
023	43	RCL
024	11	11
025	85	+
026	43	RCL
027	10	10
028	54	)
029	95	=
030	42	STO
031	10	10
032	43	RCL
033	11	11
034	55	÷
035	43	RCL
036	12	12
037	94	+/-
038	95	=
039	42	STO
040	11	11
041	92	RTN
042	76	LBL
043	11	A
044	01	1
045	75	-
046	43	RCL
047	50	50
048	95	=
049	42	STO
050	40	40
051	04	4
052	94	+/-
053	35	1/X
054	55	÷
055	43	RCL
056	36	36
057	95	=
058	42	STO
059	23	23
060	42	STO
061	24	24
062	55	÷
063	02	2
064	55	÷
065	43	RCL
066	38	38
067	65	×
068	53	(
069	43	RCL
070	36	36
071	85	+
072	43	RCL
073	38	38
074	54	)
075	95	=
076	44	SUM
077	23	23
078	22	INV
079	44	SUM
080	24	24
081	65	×
082	04	4
083	95	=
084	42	STO
085	25	25
086	02	2
087	35	1/X
088	94	+/-
089	55	÷
090	43	RCL
091	38	38
092	95	=
093	42	STO
094	26	26
095	03	3
096	03	3
097	42	STO
098	04	04
099	04	4
100	07	7
101	42	STO
102	07	07
103	71	SBR
104	24	CE
105	03	3
106	06	6
107	42	STO
108	04	04
109	05	5
110	07	7
111	42	STO
112	07	07
113	71	SBR
114	24	CE
115	71	SBR
116	78	Σ+
117	71	SBR
118	35	1/X
119	04	4
120	42	STO
121	00	00
122	01	1
123	00	0
124	94	+/-
125	76	LBL
126	85	+
127	74	SM*
128	00	00
129	97	DSZ
130	00	00
131	85	+
132	71	SBR
133	78	Σ+
134	71	SBR

CARD II
-continued-

```
135  35  1/X
136  04   4
137  06   6
138  42  STO
139  05   05
140  06   6
141  42  STO
142  00   00
143  01   1
144  06   6
145  42  STO
146  07   07
147  76  LBL
148  49  PRD
149  73  RC*
150  05   05
151  65   X
152  43  RCL
153  40   40
154  85   +
155  73  RC*
156  06   06
157  65   X
158  43  RCL
159  50   50
160  95   =
161  72  ST*
162  07   07
163  72  ST*
164  05   05
165  01   1
166  94  +/-
167  44  SUM
168  05   05
169  44  SUM
170  06   06
171  44  SUM
172  07   07
173  97  DSZ
174  00   00
175  49  PRD
176  71  SBR
177  35  1/X
178  43  RCL
179  41   41
180  42  STO
181  11   11
182  43  RCL
183  42   42
184  42  STO
185  12   12
186  43  RCL
187  43   43
188  85   +
189  43  RCL
190  23   23
191  95   =
192  42  STO
193  13   13
194  43  RCL
195  44   44
196  85   +
197  43  RCL
198  24   24
199  95   =
200  42  STO
201  14   14
202  71  SBR
203  35  1/X
204  43  RCL
205  36   36
206  44  SUM
207  41   41
208  44  SUM
209  43   43
210  43  RCL
211  37   37
212  44  SUM
213  42   42
214  44  SUM
215  44   44
216  43  RCL
217  45   45
218  35  1/X
219  85   +
220  43  RCL
221  25   25
222  95   =
223  35  1/X
224  85   +
225  43  RCL
226  38   38
227  95   =
228  42  STO
229  45   45
230  43  RCL
231  46   46
232  35  1/X
233  85   +
234  43  RCL
235  26   26
236  95   =
237  35  1/X
238  85   +
end side 1-239  43  RCL
240  38   38
241  95   =
242  42  STO
243  46   46
244  25  CLR
245  99  PRT
246  98  ADV
247  91  R/S
248  76  LBL
249  24  CE
250  03   3
251  42  STO
252  00   00
253  76  LBL
254  53   (
255  43  RCL
256  04   04
257  75   -
258  01   1
259  95   =
260  72  ST*
261  00   00
262  42  STO
263  04   04
264  97  DSZ
265  00   00
266  53   (
267  73  RC*
268  01   01
269  75   -
270  43  RCL
271  36   36
272  95   =
273  42  STO
274  10   10
275  73  RC*
276  02   02
277  75   -
278  43  RCL
279  37   37
280  95   =
281  42  STO
```

CARD II
-continued-

282	11	11
283	71	SBR
284	22	INV
285	73	RC*
286	03	03
287	75	-
288	43	RCL
289	38	38
290	95	=
291	35	1/X
292	42	STO
293	13	13
294	06	6
295	42	STO
296	00	00
297	76	LBL
298	54	)
299	43	RCL
300	07	07
301	75	-
302	01	1
303	95	=
304	72	ST*
305	00	00
306	42	STO
307	07	07
308	97	DSZ
309	00	00
310	54	)
311	43	RCL
312	10	10
313	72	ST*
314	01	01
315	75	-
316	43	RCL
317	23	23
318	95	=
319	72	ST*
320	03	03
321	43	RCL
322	11	11
323	72	ST*
324	02	02
325	75	-
326	43	RCL
327	24	24
328	95	=
329	72	ST*
330	04	04
331	43	RCL
332	13	13
333	75	-
334	43	RCL
335	25	25
336	95	=
337	35	1/X
338	72	ST*
339	05	05
340	43	RCL
341	13	13
342	75	-
343	43	RCL
344	26	26
345	95	=
346	35	1/X
347	72	ST*
348	06	06
349	92	RTN
350	76	LBL
351	78	Σ+
352	73	RC*
353	01	01
354	42	STO
355	11	11
356	73	RC*
357	02	02
358	42	STO
359	12	12
360	73	RC*
361	03	03
362	42	STO
363	13	13
364	73	RC*
365	04	04
366	42	STO
367	14	14
368	92	RTN
369	76	LBL
370	35	1/X
371	43	RCL
372	13	13
373	85	+
374	43	RCL
375	14	14
376	95	=
377	42	STO
378	07	07
379	65	×
380	43	RCL
381	11	11
382	75	-
383	43	RCL
384	12	12
385	33	X^2
386	42	STO
387	08	08
388	65	×
389	02	2
390	95	=
391	42	STO
392	09	09
393	35	1/X
394	65	×
395	43	RCL
396	07	07
397	95	=
398	72	ST*
399	01	01
400	43	RCL
401	12	12
402	94	+/-
403	55	÷
404	43	RCL
405	09	09
406	95	=
407	72	ST*
408	02	02
409	43	RCL
410	11	11
411	65	×
412	43	RCL
413	13	13
414	75	-
415	43	RCL
416	08	08
417	95	=
418	55	÷
419	53	(
420	53	(
421	43	RCL
422	13	13
423	75	-
424	43	RCL
425	14	14
426	54	)
427	65	×
428	43	RCL

CARD II
-continued-

```
429  09  09
430  54  )
431  42  STO
432  09  09
433  95  =
434  72  ST*
435  03  03
436  43  RCL
437  08  08
438  75  -
439  43  RCL
440  11  11
441  65  ×
442  43  RCL
443  14  14
444  95  =
445  55  ÷
446  43  RCL
447  09  09
448  95  =
449  72  ST*
450  04  04
451  92  RTN
```

NOTE: Intermediate results are stored in the following registers.

EZERO		CSTAR	
Reg 21:	$E_{11} = E_{22} = 0$	Reg 41:	C_{11}
22:	$E_{12} = E_{13} = 0$	42:	$C_{12} = C_{13}$
23:	E_{33}	43:	$C_{22} = C_{33}$
24	E_{23}	44:	C_{23}
25	E_{44}	45:	C_{44}
26	$E_{55} = E_{66}$	46:	$C_{55} = C_{66}$

C A R D III

Input Orientation Factor (f) and Planar Averaging

Labels Used

001	11	A
014	12	B
266	22	INV

Program

000	76	LBL
001	11	A
002	42	STO
003	17	17
004	02	2
005	01	1
006	69	OP
007	04	04
008	43	RCL
009	17	17
010	69	OP
011	06	06
012	91	R/S
013	76	LBL
014	12	B
015	02	2
016	65	×
017	43	RCL
018	17	17
019	95	=
020	42	STO
021	18	18
022	94	+/-
023	85	+
024	07	7
025	95	=
026	65	×
027	43	RCL
028	18	18
029	55	÷
030	05	5
031	55	÷
032	53	(
033	04	4
034	75	-
035	43	RCL
036	18	18
037	54	)
038	95	=
039	42	STO
040	18	18
041	94	+/-
042	85	+
043	43	RCL
044	17	17
045	95	=
046	42	STO
047	19	19
048	01	1
049	75	-
050	43	RCL
051	17	17
052	95	=
053	42	STO
054	20	20
055	53	(
056	43	RCL
057	41	41
058	85	+
059	43	RCL
060	42	42
061	65	×
062	02	2
063	85	+
064	43	RCL
065	43	43
066	54	)
067	55	÷
068	04	4
069	95	=
070	42	STO
071	10	10
072	53	(
073	43	RCL
074	41	41
075	85	+
076	43	RCL
077	43	43
078	75	-
079	02	2
080	65	×
081	43	RCL
082	42	42
083	85	+
084	04	4
085	65	×
086	43	RCL
087	46	46
088	54	)
089	55	÷
090	08	8
091	95	=
092	42	STO
093	09	09
094	53	(
095	43	RCL
096	42	42
097	85	+
098	43	RCL
099	44	44
100	54	)
101	55	÷
102	02	2
103	65	×
104	43	RCL
105	20	20
106	95	=
107	42	STO
108	08	08
109	85	+
110	43	RCL
111	42	42
112	65	×
113	43	RCL
114	17	17
115	95	=
116	42	STO
117	13	13
118	43	RCL
119	08	08
120	85	+
121	43	RCL
122	44	44
123	65	×
124	43	RCL
125	17	17
126	95	=
127	42	STO
128	15	15
129	43	RCL
130	45	45
131	85	+
132	43	RCL
133	46	46
134	95	=
135	55	÷
136	02	2
137	65	×
138	43	RCL
139	20	20

CARD III
-continued-

140	95	=
141	42	STO
142	07	07
143	85	+
144	43	RCL
145	45	45
146	65	×
147	43	RCL
148	17	17
149	95	=
150	42	STO
151	27	27
152	43	RCL
153	07	07
154	85	+
155	43	RCL
156	46	46
157	65	×
158	43	RCL
159	17	17
160	95	=
161	42	STO
162	28	28
163	43	RCL
164	46	46
165	75	-
166	43	RCL
167	09	09
168	95	=
169	65	×
170	05	5
171	65	×
172	43	RCL
173	19	19
174	85	+
175	43	RCL
176	20	20
177	65	×
178	53	(
179	43	RCL
180	10	10
181	85	+
182	43	RCL
183	09	09
184	54	)
185	95	=
186	42	STO
187	06	06
188	85	+

189	43	RCL
190	41	41
191	65	×
192	43	RCL
193	17	17
194	95	=
195	42	STO
196	11	11
197	43	RCL
198	06	06
199	85	+
200	43	RCL
201	43	43
202	65	×
203	43	RCL
204	17	17
205	95	=
206	42	STO
207	14	14
208	43	RCL
209	17	17
210	65	×
211	04	4
212	75	-
213	43	RCL
214	18	18
215	65	×
216	05	5
217	95	=
218	42	STO
219	05	05
220	43	RCL
221	10	10
222	75	-
223	43	RCL
224	09	09
225	75	-
226	43	RCL
227	42	42
228	95	=
229	65	×
230	43	RCL
231	05	05
232	85	+
233	43	RCL
234	10	10
235	75	-
236	43	RCL
237	09	09

	238	95	=
end side 1-	239	42	STO
	240	12	12
	241	43	RCL
	242	09	09
	243	75	-
	244	43	RCL
	245	46	46
	246	95	=
	247	65	×
	248	43	RCL
	249	05	05
	250	85	+
	251	43	RCL
	252	09	09
	253	95	=
	254	42	STO
	255	29	29
	256	43	RCL
	257	43	43
	258	42	STO
	259	16	16
	260	71	SBR
	261	22	INV
	262	25	CLR
	263	98	ADV
	264	91	R/S
	265	76	LBL
	266	22	INV
	267	43	RCL
	268	12	12
	269	75	-
	270	43	RCL
	271	14	14
	272	65	×
	273	43	RCL
	274	11	11
	275	55	÷
	276	43	RCL
	277	12	12
	278	95	=
	279	42	STO
	280	07	07
	281	55	÷
	282	53	(
	283	43	RCL
	284	12	12
	285	75	-
	286	43	RCL

CARD III
-continued-

287	11	11
288	65	×
289	43	RCL
290	15	15
291	55	÷
292	43	RCL
293	13	13
294	54	)
295	42	STO
296	08	08
297	95	=
298	42	STO
299	10	10
300	94	+/-
301	85	+
302	01	1
303	95	=
304	55	÷
305	53	(
306	53	(
307	43	RCL
308	13	13
309	75	-
310	43	RCL
311	11	11
312	65	×
313	43	RCL
314	15	15
315	55	÷
316	43	RCL
317	12	12
318	54	)
319	42	STO
320	09	09
321	75	-
322	43	RCL
323	10	10
324	65	×
325	53	(
326	43	RCL
327	13	13
328	75	-
329	43	RCL
330	11	11
331	65	×
332	43	RCL
333	16	16
334	55	÷
335	43	RCL
336	13	13
337	54	)
338	54	)
339	95	=
340	42	STO
341	23	23
342	65	×
343	43	RCL
344	09	09
345	94	+/-
346	85	+
347	01	1
348	95	=
349	55	÷
350	43	RCL
351	07	07
352	95	=
353	42	STO
354	22	22
355	65	×
356	43	RCL
357	12	12
358	94	+/-
359	85	+
360	01	1
361	75	-
362	43	RCL
363	13	13
364	65	×
365	43	RCL
366	23	23
367	95	=
368	55	÷
369	43	RCL
370	11	11
371	95	=
372	42	STO
373	21	21
374	01	1
375	75	-
376	43	RCL
377	22	22
378	65	×
379	43	RCL
380	07	07
381	95	=
382	55	÷
383	53	(
384	43	RCL
385	15	15
386	75	-
387	43	RCL
388	13	13
389	65	×
390	43	RCL
391	14	14
392	55	÷
393	43	RCL
394	12	12
395	54	)
396	95	=
397	42	STO
398	25	25
399	94	+/-
400	65	×
401	43	RCL
402	13	13
403	75	-
404	43	RCL
405	11	11
406	65	×
407	43	RCL
408	22	22
409	95	=
410	55	÷
411	43	RCL
412	12	12
413	95	=
414	42	STO
415	24	24
416	43	RCL
417	11	11
418	94	+/-
419	65	×
420	43	RCL
421	23	23
422	75	-
423	43	RCL
424	12	12
425	65	×
426	43	RCL
427	25	25
428	95	=
429	55	÷
430	43	RCL
431	13	13
432	95	=
433	42	STO
434	26	26
435	92	RTN

CARD III
-continued-

NOTE: Intermediate results for the Average CSTAR are stored in the following registers

Reg 21: C_{11}

22: C_{12}

23: C_{13}

24: C_{22}

25: C_{23}

26: C_{33}

27: C_{44}

28: C_{55}

29: C_{66}

C A R D IV

Conversion of C^* to Engineering Constants

Program

000	76	LBL
001	11	A
002	43	RCL
003	21	21
004	35	1/X
005	42	STO
006	11	11
007	94	+/-
008	65	×
009	43	RCL
010	22	22
011	95	=
012	42	STO
013	12	12
014	43	RCL
015	11	11
016	94	+/-
017	65	×
018	43	RCL
019	23	23
020	95	=
021	42	STO
022	13	13
023	43	RCL
024	24	24
025	35	1/X
026	42	STO
027	14	14
028	65	×
029	43	RCL
030	25	25
031	94	+/-
032	95	=
033	42	STO
034	15	15
035	43	RCL
036	26	26
037	35	1/X
038	42	STO
039	16	16
040	01	1
041	07	7
042	00	0
043	02	2
044	69	OP
045	04	04
046	43	RCL
047	11	11
048	71	SBR
049	95	=
050	01	1
051	07	7
052	00	0
053	03	3
054	69	OP
055	04	04
056	43	RCL
057	14	14
058	71	SBR
059	95	=
060	01	1
061	07	7
062	00	0
063	04	4
064	69	OP
065	04	04
066	43	RCL
067	16	16
068	71	SBR
069	95	=
070	98	ADV
071	04	4
072	02	2
073	00	0
074	02	2
075	00	0
076	03	3
077	69	OP
078	04	04
079	43	RCL
080	12	12
081	71	SBR
082	95	=
083	04	4
084	02	2
085	00	0
086	02	2
087	00	0
088	04	4
089	69	OP
090	04	04
091	43	RCL
092	13	13
093	71	SBR
094	95	=
095	04	4
096	02	2
097	00	0
098	03	3
099	00	0
100	04	4
101	69	OP
102	04	04
103	43	RCL
104	15	15
105	71	SBR
106	95	=
107	98	ADV
108	02	2
109	02	2
110	00	0
111	03	3
112	00	0
113	04	4
114	69	OP
115	04	04
116	43	RCL
117	27	27
118	71	SBR
119	95	=
120	02	2
121	02	2
122	00	0
123	02	2
124	00	0
125	04	4
126	69	OP
127	04	04
128	43	RCL
129	28	28
130	71	SBR
131	95	=
132	02	2
133	02	2
134	00	0
135	02	2
136	00	0
137	03	3
138	69	OP
139	04	04
140	43	RCL
141	29	29
142	71	SBR
143	95	=
144	98	ADV
145	98	ADV

CARD IV
-continued-

```
146   25 CLR
147   92 RTN
148   76 LBL
149   95  =
150   58 FIX
151   03  03
152   52 EE
153   95  =
154   69 OP
155   06  06
156   58 FIX
157   09  09
158   22 INV
159   52 EE
160   95  =
161   92 RTN
```

side 1 only